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Real Time Performance of Generation 2 RFID Systems in Industry and Logistics

Master's Thesis

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TEKNILLINEN KORKEAKOULU Informaatio- ja luonnontieteiden tiedekunta Tietotekniikan tutkinto-ohjelma	DIPLOMITYÖN TIIVISTELMÄ
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Työn nimi Gen2 UHF RFID järjestelmien reaaliaikanen suorituskyky teolliuuden ja logistiikan sovelluksissa	
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Tiivistelmä:

Radiotaajuinen etätunnistus (RFID) on kehittynyt viimeisten vuosien aikana ja erityisesti alan laajempi standardisointi sekä uuden sukupolven passiivisten tunnisteiden tulo markkinoille on herättänyt kiinnostusta käyttää tekniikkaa monissa eri tunnistussovelluksissa. UHF-taajuusalaueella toimivat passiviset uuden sukupolven Gen2-tunnisteet on suunniteltu teollisuuden ja logistiikan käyttökohteisiin, erityisesti toimitusketjun hallintaan liittyviin sovelluksiin, kuten esimerkiksi kuormalajvojen tunnistukseen. Gen2-tunnisteita on myös mahdollista käyttää vaativimmissakin sovelluksissa perinteisten käyttökohteiden ulkopuolella. Gen2-järjestelmien soveltuvuutta vaikeampien reaaliaikaisten prosessien osaksi on tutkittu tässä diplomityössä.

Gen2 RFID-järjestelmien suorituskykyä reaaliaikaisissa sovelluksissa analysoitiin sekä teoreettisella että käytännön tasolla. Nykyisin markkinoilla olevia lukijalaitteita testattiin ja erilaisten parametrien vaikutusta mitattiin vasteaikoihin niin luku- kuin kirjoitusnopeuden suhteen. Työssä tarkasteltiin myös dataa eräistä tuotantokäytössä olevista prosesseista, joissa käytetään Gen2 UHF RFID tekniikkaa, pyrkimykenä selvittää, miten järjestelmät suorituvat käytännössä teollisuuden sovelluksissa.

Työn tuloksena kehitettiin mm. ohjelmisto, jolla voitiin helpommin mitata ja analysioda lukijoiden vasteaikoja lukunopeuden suhteen. Mittaustuloksia saatiin niin laboratoriomittauksista, kuin oikeista teollisuuden sovelluksistakin. Työn tuloksena voitiin todeta Gen2-järjestelien soveltuvan hyvin moniin reaaliaiakaisuutta vaativiin sovelluksiin, mutta myös havaittiin muutamia tilanteita, joissa tekniikan heikot kohdat tulevat esille.

Avainsanat: UHF, RFID, Etätunnisteet, Radiotaajuinen tunnistus, EPC, Gen2, Reaaliaikaset järjestelmät

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Abstract:

Radio frequency identification (RFID) has received a great deal of attention over the past couple of years. The development especially in standardization and the introduction of the next generation long range passive tags has made the technology more interesting to all levels of identification. Passive long range Generation 2 (Gen2) technology has been seen as a promising technology for applications in manufacturing industry and logistics. Supply chain tracking and tracing and product identification are the most common Gen2 applications. Having realized the potential of RFID systems, companies and industries are looking at implementing Gen2 systems also on areas outside typical Gen2 applications. The main purpose and objective of the thesis is to study the currently Gen2 based RFID systems and find out what are the capabilities and constraints in terms of real time applications.

In this thesis work real time performance of Gen2 RFID was studied on theoretical and practical level. Measurements were done in lab environment and a test setup was developed for benchmarking currently available reader devices and their different RF level parameter choices. Also real industrial processes that are using Gen2 technology in real time applications were investigated in order to find out performance of Gen2 systems in today's real life applications.

As a result of the thesis work a software application was developed for easier testing and visualization of RFID reader's performance. Response rates for several different test cases proved that Gen2 systems can be used in several real time application requiring fast response times. Theoretical analysis and the long response times of some system level test cases revealed also weak points of RFID systems regarding real time applications.

Keywords: UHF, RFID, EPC, Gen2, Real time systems, Radio frequency identification

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GLOSSARY

ALE = Application Level Events

AUTO-ID = Automatic Identification

GEN2 = Generation 2 UHF RFID Specification by EPCglobal

EPC = Electronic Product Code

EPCglobal = The Electronic Product Code standardization body

EPCIS = EPC Information Services

ERP = Enterprise Resource Planning

ETSI = European Telecommunications Standards Institute

FHSS = Frequency Hopping Spread Spectrum

HF = High Frequency

ISO = International Standardization Organization

LBT = Listen Before Talk

LF = Low Frequency

LLRP = Low Level Reader Protocol

MW = Middleware

RFID = Radio Frequency Identification

RP = Reader Protocol

UHF = Ultra High Frequency

1 INTRODUCTION

Radio Frequency Identification (RFID) is a general term for a technology that uses radio-frequency waves to transfer data with a device known as a RFID tag. An RFID tag contains data in a silicon chip that can be read and written remotely. RFID enabled communication between readers and movable tagged objects creates a possibility to identify, inventory and track items automatically, fast, reliably and with no line of sight [11]. Contactless identification of objects and transfer of data has become lately very popular in a wide range of industries and applications, mainly in logistics, manufacturing, transportation and material flow [p1, 12][36]. RFID as a technology seems to be becoming mainstream as more and more large companies start large deployments and also major vendors appear to the market. According to sources such as [57] there is significant growth in the RFID market: $1.8 billion RFID tags have been sold in 2005 and the estimate for 2015 is $24.5 billion.

RFID is an automatic identification (Auto-ID) technology meaning that RFID systems provide information of tagged objects in an automated way. Automatic identification is generally used to automate processes and reduce the amount of time and labor needed for humans to recognize and manually input data about an object [18, 19].

RFID has received a great deal of attention over the past couple of years. The development especially in standardization and the introduction of the next generation long range passive tags has made the technology more interesting to all levels of identification. Cost effective, passive long range RFID technology such as the EPCglobal Class 1 Generation 2 (Gen2 or EPC Gen2) has been seen as a promising technology for logistics applications and for supply chain tracking and tracing especially. The fact that some large commercial companies and government bodies, such as Wal-Mart and Target in the United States, Tesco in Europe, and the U.S. Department of Defense, decided to adopt RFID technology and re-engineered their supply chains to take advantage of this new automatic identification technology has been one main reason for a attention. The announcements of RFID mandates from these companies requiring also their suppliers to implement RFID pushed the technology further down in supply chains to other companies also [13][36][56].

As the price and availability of low cost and long range UHF Gen2 tags improves with growing markets the technology comes more and more attractive to other implementation cases also, besides basic logistics. In some cases the enthusiasm of RFID vendors and companies wanting to take advantage of new technology has even resulted in somewhat misleading expectations of the technology [p2, 20] and where it can be applied – especially in applications where true real time operation is required. The challenges in designing reliable Gen2 RFID systems are in cases such as:

- Managing multi reader environments
- Identification of fast moving objects
- Identification in multi tag environments

For implementers of Gen2 RFID systems, there seems to be currently some lack of data and information about the performance of Gen2 systems in real life production environment. This thesis aims to characterize the performance of current Gen2 UHF RFID systems, focusing on the real time environments that require fast response times and reliability. I intend to focus mostly on two typical responses common in RFID systems: The time needed for reading tags and return channel response time, meaning how long it takes to complete an action after identification. The results of this thesis aim to finding out optimal ways to implement Gen2 RFID in different cases.

1.1 EPCglobal Class 1 Generation 2 UHF RFID

EPCglobal Inc. is an independent non-profit standards organization, previously known as Auto-ID Center that is driving the standardization work and implementation of EPC technology and EPCglobal Network infrastructure. Their standards and specifications cover a wide range of RFID related data, communication and programming techniques [13].

There are many different RFID tag types and technologies available, varying in frequency ranges, types and standards, but in this thesis I mainly focus on the EPC Gen2 UHF technology. The Class 1 Generation 2 tag standard was ratified late 2004 and it is a result of over 40 companies of the industry trying to create a standard with cross-vendor compatibility, worldwide interoperability, improved performance compared to previous tag generations, reliability and low cost. Some examples of the improvements of the new generation tags are that the first tag generations, such as EPC Class 1 and 0. ISO18006a/b and others have had generally data rates around 55 to 80kbps, Gen2 has up to 640kbps resulting in read rates of hundreds of tags per second. Gen2 can be used worldwide between 860 and 960 MHz frequency band, depending on the region, but the tag itself is “global” – only reader equipment is specific to region. Gen2 tags are designed to be as cost effective, with small amounts of memory for small chip size [13]. The advantages of Gen2 tags compared to other tag types and the availability of various Gen2 tags for different applications and from a number of vendors have made it widely adopted [13].

EPCglobal standards and Gen2 protocol will be described more in detail in further on in this thesis.

1.2 Real time RFID systems

A system is said to be real time if the total correctness of an operation depends not only upon its logical correctness, but also upon the time in which it is performed [16]. The classical conception is that in hard real time systems operations that occur after a hard after deadline may lead to a critical failure of the complete system. A soft real-time system on the other hand will tolerate such lateness, and may only respond with decreased service quality (e.g., dropping frames while displaying a video) [16].

In many areas and applications where RFID technology is used there is also a real time requirement present. It can be for example a vehicle tracking system or toll collection from moving vehicles. Identification of items on a non stopping conveyor belt in manufacturing or perhaps real time personnel tracking for security control are also considered to be real time systems.

Logistics has been a major driver for passive UHF RFID technology and many of the logistics applications actually do require certain (soft) real time requirements to meet the business cases and for example tracking capabilities. Especially in manufacturing one fundamental question is how to produce accurate real time data, allowing more efficient forecasting, production and distribution operations [10]. Also in manufacturing the requirements for real time operation are in many cases considerably higher. Thus far RFID technology has already been used in many areas of manufacturing and as one identification method on production lines, but mostly with older HF technologies, that have been specifically designed for manufacturing use. This brings up one of the main questions here when considering Gen2 UHF RFID in real time applications, and in manufacturing: Gen2 UHF RFID standards are based on mainly the needs of logistics applications, aiming for low cost tags and long reading range. Gen2 was not necessarily developed for true 100% reliability, deterministic response time and controlled environments. However, Gen2 RFID tags are still making their way to manufacturing applications, one main reason being the low cost of tags and standardized off-the-shelf devices.

A key issue in developing automatic identification technology in is the requirement for a supporting information infrastructure. Large scale RFID systems generate massive amounts of item level identification events and handling such amount of data effectively and economically is crucial – especially in real time systems where the deadlines for identification are strict. Equally important is the investigation of different routes along which this information passes – from sensing of tags to final use in business applications – so as to guarantee that only the right amount of information is retrieved at a particular location and that it will be available in time where needed. When real time control systems are linked to RFID identification, it is crucial that the systems won't be overloaded and can maintain an acceptable response time. [7]

1.3 Scope and objectives of the research

The main purpose and objective of the thesis work is study the currently widely adopted EPC Gen2 based RFID technologies and systems and find out what are the capabilities and constraints in terms of real time operability. The objectives focus around the question:

- How can fast response times and reliability be achieved with Gen2 RFID technology?
- What kind of design is required in real time RFID system implementations?
- What are the real time capabilities of current RFID systems?

The research will focus in finding RFID solutions that will provide fast response times, reliability and predictability, still offering good maintainability and conforming to current standards in the industry. Gen2 standards, specifications and protocols are studied with the focus around response times and reliability. Especially tag reading time (low level response time) and response actions generated by a complete RFID systems (higher level response time) are measured and analyzed. Some of the current technology available is evaluated in terms of real time operability and some example cases are introduced and studied where real time operation has been achieved with different system designs.

The objective is to produce information about Gen2 RFID performance capabilities and limitations that will help design and implement RFID systems that have real time requirements.

1.4 Structure of the study

In the first part of this thesis provides background information regarding RFID technology and RFID systems. Technologies are studied from the real time requirements viewpoint and content focuses around RFID systems in logistics and manufacturing.

Previous research and existing solutions are studied, some of the current RFID hardware and software on the market is evaluated and their performance is measured to determine abilities of these systems. Based on the research and assessment of the capabilities of the hardware and software component available today, I will try to determine what the key issues are when fast real time performance is needed.

After the background research parts some real world example cases are evaluated and their design and measurement results analyzed to determine how real time performance was achieved in actual production scale RFID solutions.

2 RADIO FREQUENCY IDENTIFICATION

2.1 History

The roots and basics of RFID technology go back all the way to the discovery of radio signals. In 1906, Ernst F. W. Alexanderson demonstrated the first continuous wave transmissions of radio signals. Approximately the year 1922 was considered to be the birth of radar [15]. A radar sends out radio waves for detecting and locating an object by the reflection of the radio waves, also in RFID backscatter communication of tags bases on same principle, reflection of radio waves. Following the technical developments in radio and radar in the 1930s and 1940s also several technologies related to RFID were being explored such as the long-range transponder systems of "identification, friend or foe" (IFF) for aircraft [15], which is often referred as the first use of RFID technology. It was invented by the British in 1939 to identify airplanes [20] during the World War II . Developments of the 1950s include such works as D.B. Harris', "Radio transmission systems with modulating passive responder" [15]. Commercial activities were beginning in the 1960s. Electronic article surveillance (EAS) equipment was developed to counter theft for example [15]. EAS systems are (often) 1-bit tags that are only able to detect presence or absence of a tag. EAS systems used either microwave or inductive technology. EAS is the first and most widespread commercial use of RFID [15]. Animal tracking, vehicle tracking, and factory automation applications were developed in the 1970s and 1980s. They were shortly followed by electronic toll collection and access control [15]. In the 1990s there was a growing interest of RFID into the item management work and the opportunity for RFID to work along side bar code [15].

According to [57] the defining moments of recent RFID history are for example the forming of Auto-ID labs by MIT in 1999, Gillette's and Walmart's big RFID efforts in 2003, DoD (Department of Defense) adapting RFID in 2004 and the developments in reader and antenna technology by Impinj in 2006.

2.2 Physical backgrounds in radio frequency technology

Communication in RFID systems is based on electromagnetic waves. Electromagnetic wave is a self-propagating wave in space that has electric and magnetic components. Electric and magnetic fields oscillate in phase perpendicular to each other and to the direction of energy propagation. RFID systems (close range) using inductive coupling take advantage of the magnetic field and electric field can be used with (long range) electric coupling backscatter systems.

RFID tags are energized by a time-varying electromagnetic radio frequency (RF) wave, carrier signal that is transmitted by the reader. Carrier signal provides power for the tag as long as the antenna stays in the RF field generated by the reader and the communication between reader and tag is based on modulating the carrier signal [33].

Electromagnetic radiation is classified into types according to the frequency of the wave. RFID uses radio waves that are generally between the frequencies of 30 KHz and 5.8 GHz, but the Gen2 standard is based on UHF frequency range from 860 MHz to 950 MHz

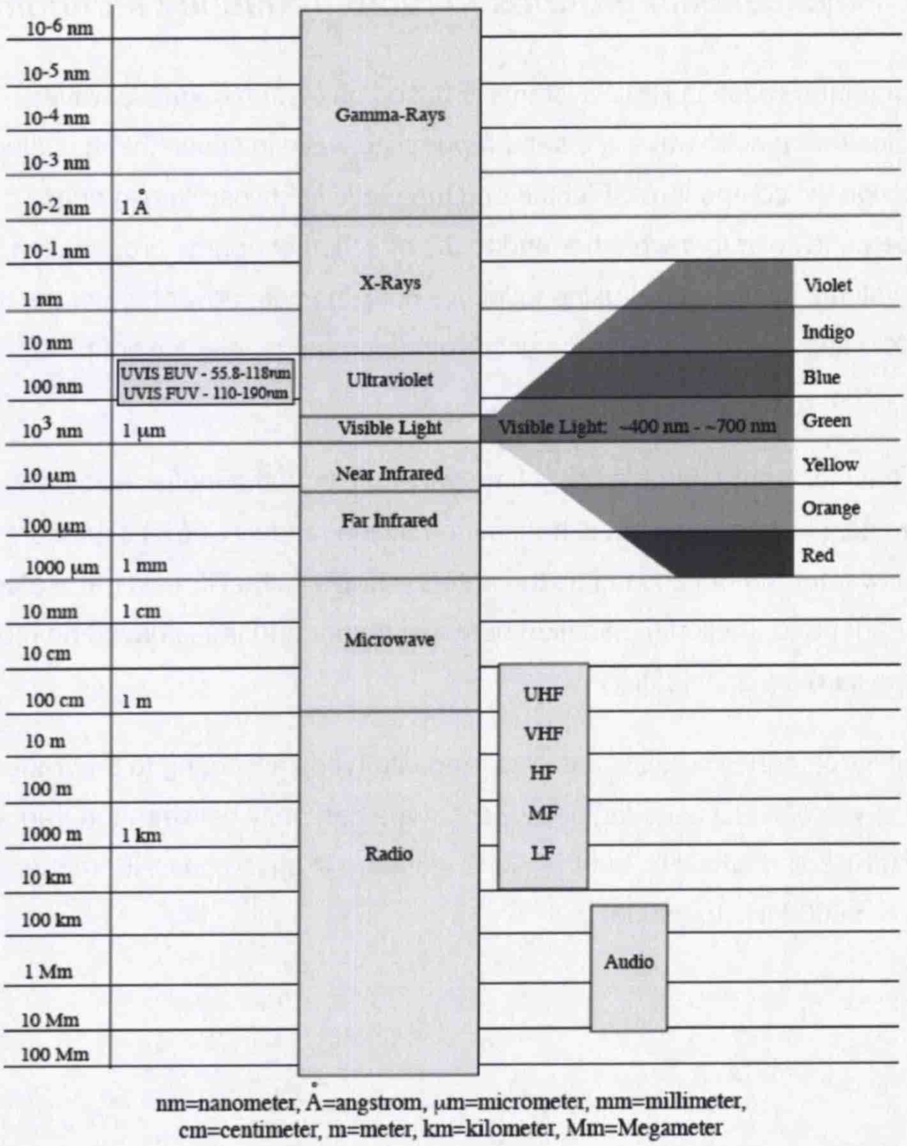

Figure 1. Electromagnetic Spectrum [34]

Frequency of the waves correlate to the wavelength as can be seen in the Figure 1. Electromagnetic Spectrum [34], and it is based on the equation:

$$v = f\lambda$$

Where v is the speed of the wave (c in a vacuum, or less in other media), f is the frequency and λ is the wavelength. For example for European Gen2 systems (868 MHz) the wavelength would be about 34,5cm. This in turn is an important design criteria for RFID antennas – e.g. a half-wave dipole is a very common type for RFID tag antennas.

2.3 Development of technology

The abbreviation RFID stands for *radio frequency identification* and it is used today as a generic term for technologies that use radio waves for identification. RFID is an automatic identification technology that has many advantages in comparison to other forms of automatic identification, such as barcode systems, fingerprint identification, voice identification or smart cards. Contactless, non optical, transfer of data makes it much more flexible to than smart cards (bank cards for example) or barcodes, it has ability store more information than many of the other identification methods, the read rates and speeds are fast and the cost of tags is also low as mass markets are adopting the technology.

Technology	Physical size	Lifespan	Data density	Reading speed	Reading distance	Reusability	Cost
UHF Gen2 RFID Passive, ~860-950Mhz	Small, depends on antenna size -> range	Unlimited shelf life	Very high (up to 64k bytes)	Very fast (>100 / s)	~0-10m	Yes	Low
Active RFID, 2.4Ghz	Larger than passive tags	Limited by battery life	Very high	Very fast (>100 / s)	0-100m	Yes	Medium
Barcode	Larger than RFID tags, sensitive to the aspect ratio for presentation to a scanner	Unlimited shelf life but barcode subject to degradation with handling	Low (1-100 bytes)	Low	0-0.5m	No	Very low

Table 1 Comparison of different identification technologies [12, pages 3-8][17]

2.4 Other similar identification techniques

Discrete sensing, barcode reading, optical and acoustic identification methods have been mostly used for identification in manufacturing [7]. Discrete sensing mechanisms are able to detect the presence of product on a specific location. Examples range from a mechanical or proximity switch to more sophisticated infrared or laser sensors. Barcodes and discrete sensing is used for applications such as, tracking or sorting of products on conveyors; identifying raw-materials used in product assembly, assessing work-in-process inventory [7]. In barcode systems usually only one item can be read at a time. The items must also be arranged in a fashion that bar-codes could be located right in front of the scanner. Moreover the speed at which scanning can be accomplished also limits the speed of conveyors or items moving along material handling systems. Harsh manufacturing environments such as chemicals conditions may also hamper the barcode labels thus making them unreadable [7].

2.4.1 Comparison to barcode

RFID is relatively similar concept to bar coding. The barcode is a binary form of code, and it comprises of wide and narrow fields of bars and gaps. Fields and gaps represent numbers which are arranged according to a coding type. Barcode is read optically with a laser and the black and white areas can be detected by the amount of reflected light [12], naturally barcode has to be in the field of view of the scanner.

Figure 2 Example of (JAN13, EAN13) barcode

Figure 3 Example of data matrix barcode

Barcodes are found today on most consumer packaged goods and they contain information describing the type of an item and the identity of its manufacturer [6]. As seem in the example figure (Figure 4) also more sophisticated 2D barcodes have been developed in order to fit more data into a barcode, but still the main weakness of the barcode is low data storage capacity and the fact that it cannot be "reprogrammed" after printing. In practice the size is limited and common barcode systems do not identify objects at single item level, with a serial number, usually only with country, manufacturer and item number.

2.5 Tags

RFID transponders comprise of an electronic microchip and an antenna or coil (coupling element). They are generally known as "tags". There are both passive and active transponders available, but most common transponders do not have voltage supplies [12] and are totally passive when they are not in field of a reader signal. RFID tags combine wireless communication and a data storage capacity [6]. Line of sight is not needed as radio waves are used for communication. The most common way of implementing an RFID tag is to mount a silicon chip onto a foil antenna. Read distance ranges from a few centimeters up to 10 meters in current standards.

RFID technical constraints:

- Water and other liquids absorb radio signals (UHF)
- Reader signals (magnetic and radio) do not penetrate through metal
- Dielectric properties of the materials in the vicinity of the tag affect the performance of the tags – detuning effect (UHF)

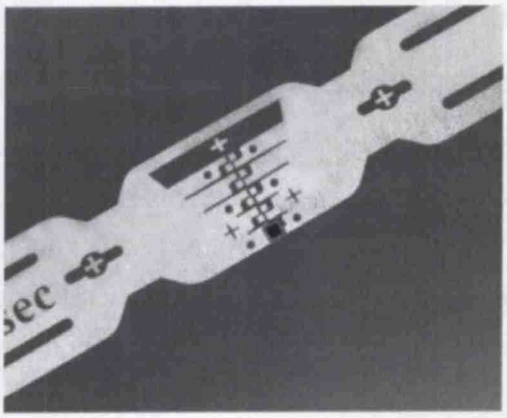

Figure 4. RFID Chip and antenna [55]

Figure 5. Hard on-metal RFID tag [55]

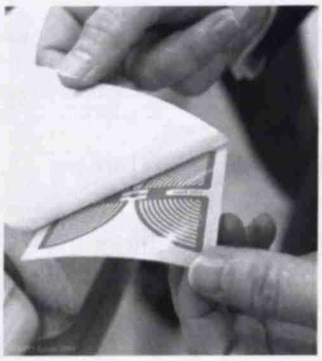

Figure 6. Back of a RFID label [55]

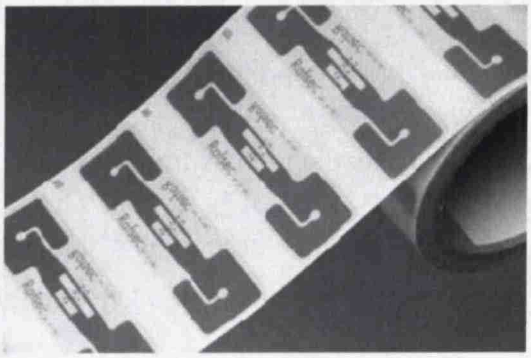

Figure 7. Roll of UPM Dogbone wideband UHF RFID tags [55]

2.6 Tag types

RFID devices have two broad general categories, active and passive, those with a power supply and those without. With passive tags the power required to activate the transponder is supplied through coupling with the reader's electrical/magnetic field. In a passive system only the reader has an external power source [6]. Passive communication is a master-slave type of system where the reader is a master that generates an RF field that powers the tags (the slaves) within range in addition to transmitting data to those tags. This type of communication has relatively high energy demands of radio transmissions and reception [6]. Active transponders usually communicate through propagation coupling and respond to the reader's transmission drawing on internal power to transmit [2].

Active tags are larger and more expensive that passive tags. The use of a battery places a limit on the life of the device, although with current battery technology this may be as much as ten years. Passive tags have an unlimited life, are lighter, smaller and cheaper. The trade off is limited data storage capability, a shorter read range and they require a higher power reader. Performance is reduced in electromagnetically “noisy” environments. There are also semi passive tags where the battery runs the chip’s circuitry but the device communicates by drawing power from the reader. Tags are available in a wide variety of shapes, sizes and protective housings. The smallest devices commercially available today measure 0.4x0.4mm and are thinner than a sheet of paper [2].

2.6.1 EPCglobal class definitions

The EPCglobal organization has classified tags in four classes according to their type. (EPCglobal and its standards will be described later on in this thesis) These basic types are defined in reference [24]. In this thesis I mainly concentrate on the class 1 type passive tags and their use and performance in different real time cases.

- Class 1: Identity tags, passive-backscatter tags with the following minimum features:
    - An electronic product code (EPC) identifier
    - A tag identifier (Tag ID)
    - A function that renders a tag permanently non-responsive
    - Optional decommissioning or re-commissioning of the tag
    - Optional password-protected access control
    - Optional user memory
- Class 2: Higher-functionality tags, passive tags with the following anticipated features above and beyond those of Class-1 tags:
    - An extended Tag ID
    - Extended user memory
    - Authenticated access control

- Additional features as will be defined in the Class-2 specification

- Class 3: Battery-Assisted Passive Tags (called Semi-Passive Tags in UHF Gen2), Passive Tags with the following anticipated features above and beyond those of Class-2 Tags:
  - A power source that may supply power to the Tag and/or to its sensors
  - Sensors with optional data logging.
  - Class-3 Tags still communicate passively, meaning that they require an Interrogator to initiate communications, and send information to an Interrogator using either backscatter or load-modulation techniques.

- Class 4: Active Tags, Active Tags with the following anticipated features:
  - An electronic product code (EPC) identifier
  - An extended Tag ID
  - Authenticated access control
  - A power source
  - Communications via an autonomous transmitter•
  - Optional User memory
  - Optional sensors with or without data logging
  - Class-4 Tags have access to a transmitter and can typically initiate communications with an Interrogator or with another Tag. Protocols may limit this ability by requiring an Interrogator to initiate or enable Tag communications. Because active tags have access to a transmitter, of necessity they have access to a power source. Class-4 Tags shall not interfere with the communications protocols used by Class-1/2/3 Tags.

2.7 Various frequencies and standards

Different radio frequencies have different properties. At low frequencies waves pass through obstacles well, but the transmit power falls quickly at longer distances. At high frequencies waves don't pass through obstacles, instead they reflect and diffract at corners, edges and openings. Interference of radio waves has to be kept at minimum otherwise electrical equipment working at the same frequencies will distract each other. Because many of the available frequencies are already in use, RFID use has to be limited to licensed frequencies, which are different in many countries [13].

Table 2. Frequency ranges generally used for RFID applications [2][32].

Frequency	Characteristics	Standards	Typical Applications
LF 100-500 kHz	• Passive. • Low reading speed. • Lower sensitivity to metals/liquids.	ISO 11784 ISO 18000-2A ISO 18000-2B	Access control, Animal ID, Car immobilizer. Early generation tags.
HF 10-15 MHz	• Passive • Medium read speed. • Medium sensitivity to metals/liquids.	ISO15693 ISO14443 ISO 18000-3	Access control, smart cards, library control.
UHF 433Mhz	• Active	ISO 18000-7	Tracking large objects e.g. containers
UHF 850-950 MHz	• Passive. • Fast read speed. • High sensitivity to metals/liquids. • Low cost	ISO18000-6A ISO18000-6B EPC Class 0 EPC Class 1 EPC Class 1 Gen2 (ISO18000-6 Type C)	Supply chain applications e.g. pallet tracking

2.4-5.8 GHz	• Active tag. • High sensitivity to metals/liquids. • Battery powered (life up to 5 years). • Expensive. • Larger size	ISO 18000-4 ISO/IEC 24730-2	Toll collection systems

Frequency	Read range	Data rates (aprox.)
LF 100-500 kHz	<50cm	~5.1 kbps
HF 10-15 MHz	<1,5m	26 kbps->
UHF 433Mhz	<70m	27.7 kbps
UHF 850-950 MHz	<10m	10-70 kbps
2.4-5.8 GHz	<100m	20-40 kbps

Table 3. RFID frequency range compared to read range.[32].

In Finland the frequencies allocated to UHF RFID use are 865-868 MHz, with a power limit of 100mW from which the band 865.6 MHz - 867.6MHz allows a 2W ERP power level. At higher frequencies 2.446 GHz- 2.454 GHz band is also allocated to RFID use (common in active RFID) with an effective transmit power limit of 500mW [20]. Some lower frequencies can also be used, 13,56 MHz for example for HF RFID.

Internationally there are differences in frequencies allocated for RFID applications although standardization through ISO and similar organizations is assisting in compatibility. For example, Europe uses in general frequencies around 868 MHz for UHF and the US uses 902-928 MHz [2]

2.8 Operating principles

Several different ways for reader – transponder communication and power transfer have been developed for different application areas and read ranges. Inductive coupling and backscatter techniques have become standard in current RFID systems.

2.8.1 Inductive coupling

Inductively coupled transponders have a large area coil that functions as an antenna. They almost always operate passively and from relatively short distance. The reader generates a string high frequency (HF) electromagnetic field that penetrates the coil area. As the distance between the reader and the coil is several times shorter than the wavelength (<135 kHz: 2400m, 13.56 MHz: 22.1m) the electromagnetic field may be treated as an alternating magnetic field and a small voltage is generated to the transponder by inductance [18]. A transformer works the same way. The efficiency of the power transfer is proportional to operating frequency, number of windings in the coil, area, angle and distance of the coils. Communication is possible by switching on and off a load resistor on the transponder, which generates changes in the impedance and voltage at the reader end. According to [18] an 80dB signal to noise ratio can be expected (100V reader antenna = 10mV at transponder).

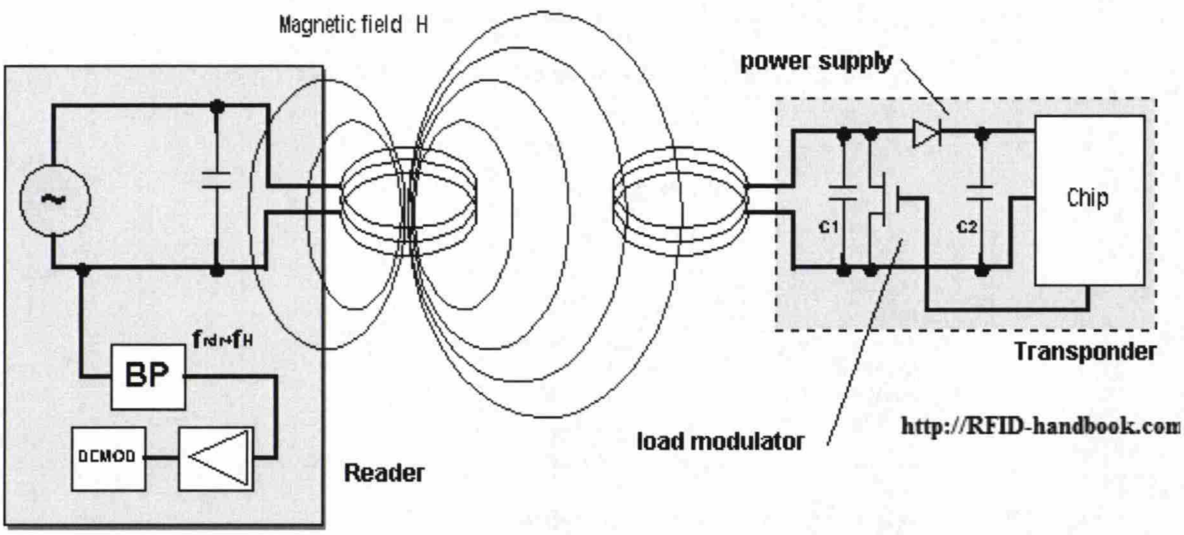

Figure 8. Inductive coupling [28]

2.8.2 Electromagnetic backscatter coupling

For distances greater than 1m shorter wavelength frequencies are needed. UHF frequencies and microwave frequencies make it possible to build long-range systems with backscatter coupling [12]. Electromagnetic waves are reflected by objects that are greater in dimension than half the wavelength. Backscatter tags have antennas that are in resonance with the signal wave of the reader. The communication is possible, because reflection characteristics can be changes by altering the load connected to the antenna [12]. By using a low power transponder chip on the tag, the power of the electromagnetic field is sufficient at distances up to 10m [12].

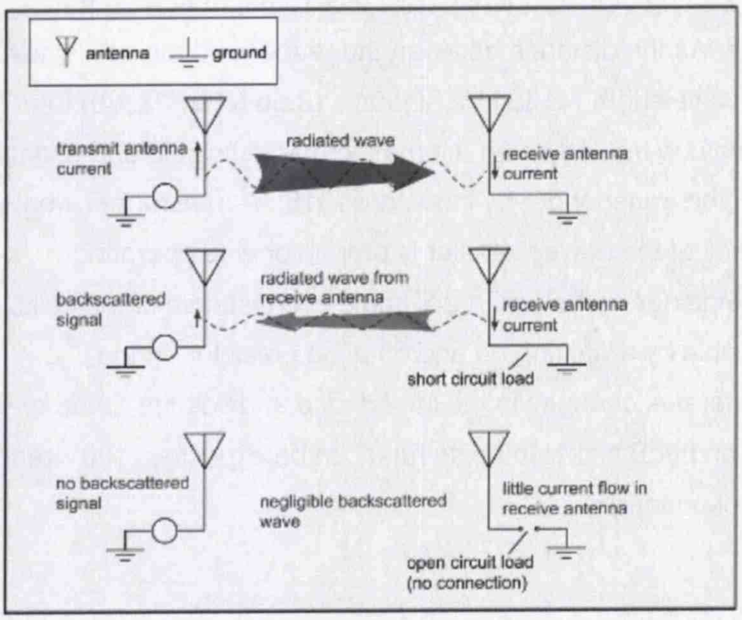

Figure 9. Backscattered wave operating principles [25]

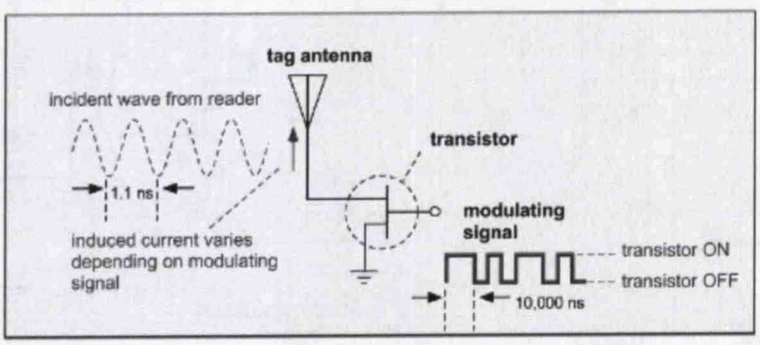

Figure 10. Modulated Backscatter [25]

2.8.3 Near field and far field communication

UHF RFID systems are basically developed for long-range systems and base on electromagnetic backscatter coupling. Compared to LF/HF systems UHF performance in general is more susceptible to the presence of various dielectric and conducting objects in the tag vicinity. In LF/HF short range systems, communication is based on inductive coupling between the reader and the tag antennas through a magnetic field, which improves performance in such conditions, but also limits the operating range and thus LF/HF systems can only operate on relatively short range. Near field coupling can also be used in UHF RFID applications for better operation for shorter ranges [27].

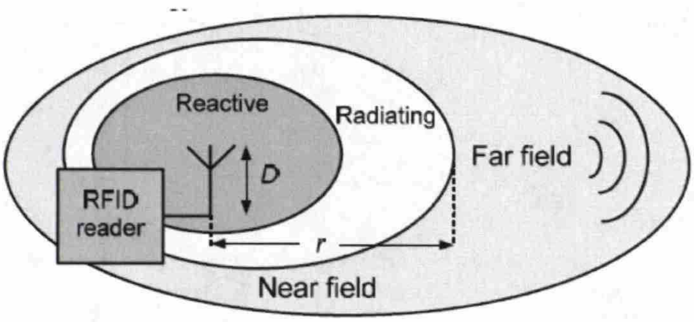

Figure 11. Near field and far field [27]

The Figure 11 shows three regions in the antenna field: *Radiating*, where the angular field distribution is dependent on the distance and *reactive*, where the energy is stored but not radiated. They are both near field areas and use inductive or capacitive coupling in the magnetic or electric near field. Far field area, having the longest range, is based on backscatter coupling in the electric field. Electric and magnetic fields are perpendicular to each other and the direction of propagation. The boundary between the far field and the near field region depend on the antenna design, but it can be estimated by the equation r = 2D2 /λ where D is the maximum antenna dimension and is the wavelength [27].

The primary advantage in using near field for UHF RFID is the ability to read tags in RF non-friendly scenarios, such as with liquids for example. In near field the intensity is much stronger compared to far field and less minimum power is required to activate the tag [27].

Currently there are tags on the market that have been specially designed to be used in near field and also tags that are able to operate in both near field and far field. Near field tags they can be smaller in size than typical far field tags, because only a small loop like antenna construction is required. The tags that can operate in both usually combine the loop like structure with a larger dipole antenna.

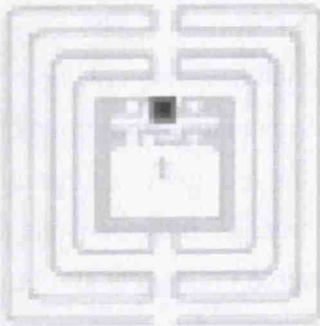

Figure 12. UPM Raflatac EPC Class1 Gen2 "Mini" tag (Antenna size: 21 x 21 mm) [29]

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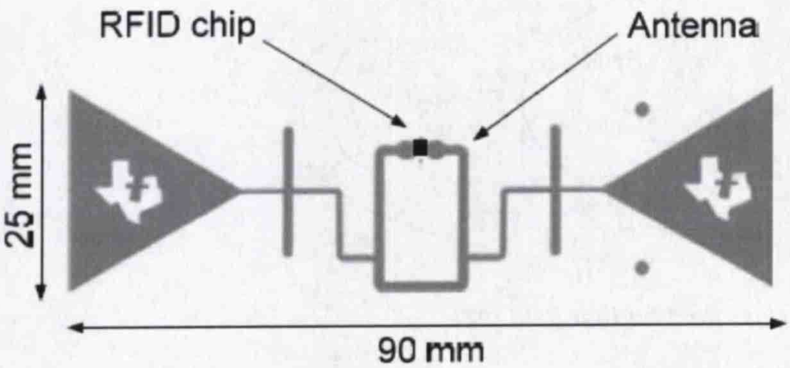


Figure 13. RFID tag with near field and far field capable antenna [27]

2.9 Protocol standards

RFID Protocol standards define how reader devices and tags communicate over the physical air interfaces that were described in earlier sections. Whether the communication is based on inductive or electromagnetic backscatter coupling, the actual communication follows a certain protocol and there are various different protocols available for different usages.

One of the newest of these protocols is the EPC Class 1 Gen2 protocol and it is the main interest of this thesis, due to its wide adaptation on the market in a range of applications [36][37][13].

Standard	Frequency	Common use	Design year
ISO14443(Mifare)	13,56Mhz (HF)	Access control, Anti-counterfeit	1995
ISO15693	13,56Mhz (HF)	Short range	1995
EPC Class 1 Gen1	860-930Mhz (UHF)	Logistics	2003
EPC Class 1 Gen2	860-930Mhz (UHF)	Logistics	2005

Table 4. Some of the RFID protocol standards

2.10 Systems

Most common RFID systems comprise of RFID tags that are used to identify objects, readers and antennas that are able to communicate with the tags and software applications that translate tag reads into meaningful events, for example in a tracking system.

Figure 14. Smart RFID Gate for reading pallet tags [55]

On the lowest level of an RFID system are of course tags and readers, the actual hardware needed for identification, but rarely any systems comprise only of the lowest level components – in order to transform data from tag reads to meaningful information a backend system is needed. Depending on the application these backend system can be actually very large and complex systems – combining the data from tag reads to other information, such as creating asset tracking events according to tag read on a RFID enabled gate combining it with a database linking tag data (e.g. serial number) to an actual asset (e.g. pallet/rollcage/etc). However, when early RFID systems were being created, such as supply chain management applications with passive RFID, the developers noticed that tags and readers produce a huge amount of data, that would overload business applications [p261 13]. One way to implement an efficient RFID system architecture was achieved by implementing a middleware layer between the readers and business applications. Its purpose is to provide useful information to business systems rather than raw tag data.

On the lowest level of a RFID system is the actual data collection hardware, for example:

- Gates equipped with RFID antennas and readers
- Conveyor belts with RFID antennas and readers
- RFID Handheld devices
- Access control readers / Desktop readers / etc
- RFID Printers

In cases where a fast response time is required and it is not possible to connect the RFID devices into to a backend system, such as in the case presented in section 6.3 (Robotics application) a standalone or so called “edge” system can be used to provide the actual response.

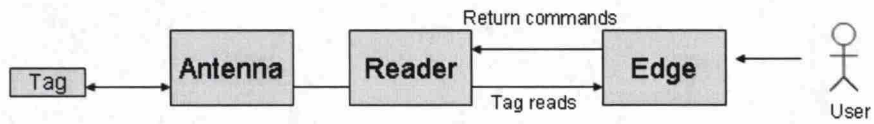
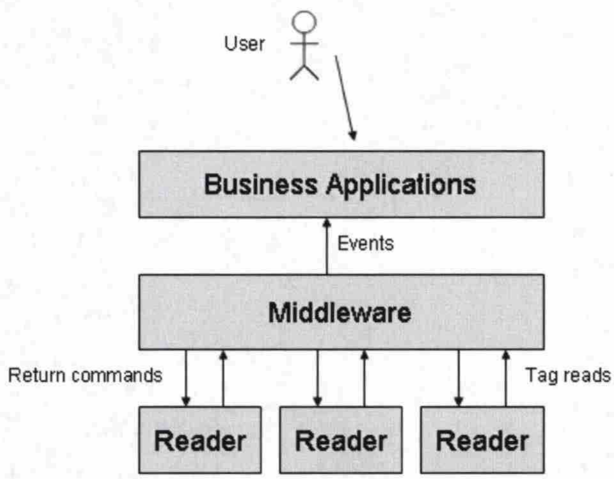


Figure 15. Standalone RFID system

Large data collection networks require middleware layers to operate efficiently. Key tasks for a RFID middleware layer are:

- Data collection
- Filtering data
- Mapping of read locations to physical locations
- Proving real events to business systems



Business applications' role is to receive the events generated by middleware and combine them with other data and provide the reports to users of that particular system. A business system can be a supply chain management application, asset tracking system or an ERP system in general.

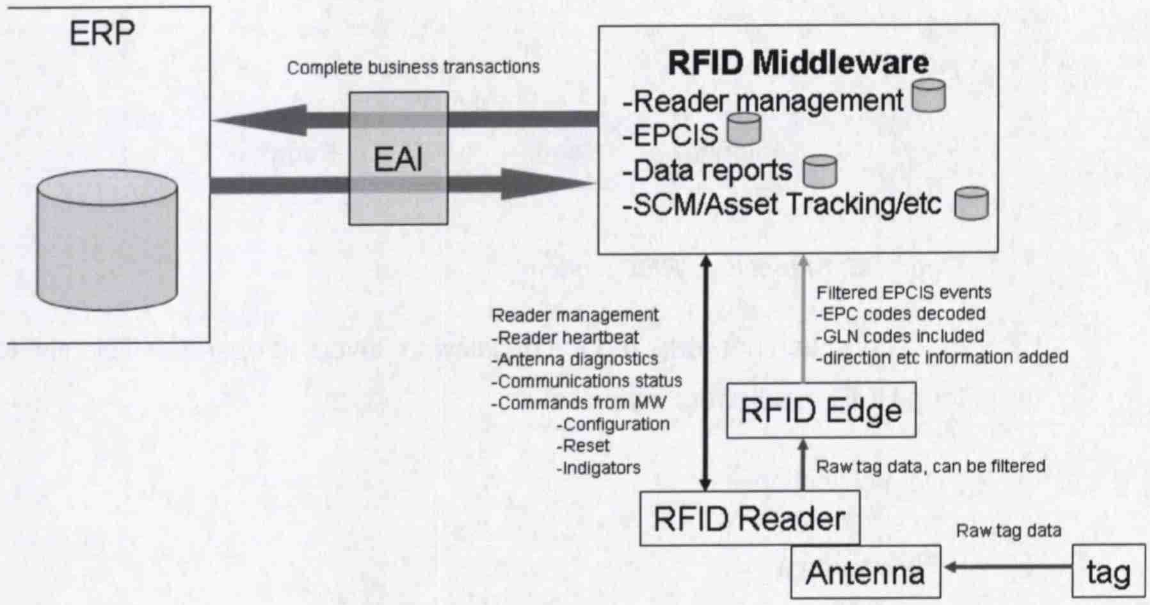


Figure 16.Model of common RFID System architectures

2.10.1 Gate applications

Figure 17.Smart RFID gate equipped with and EDGE application.

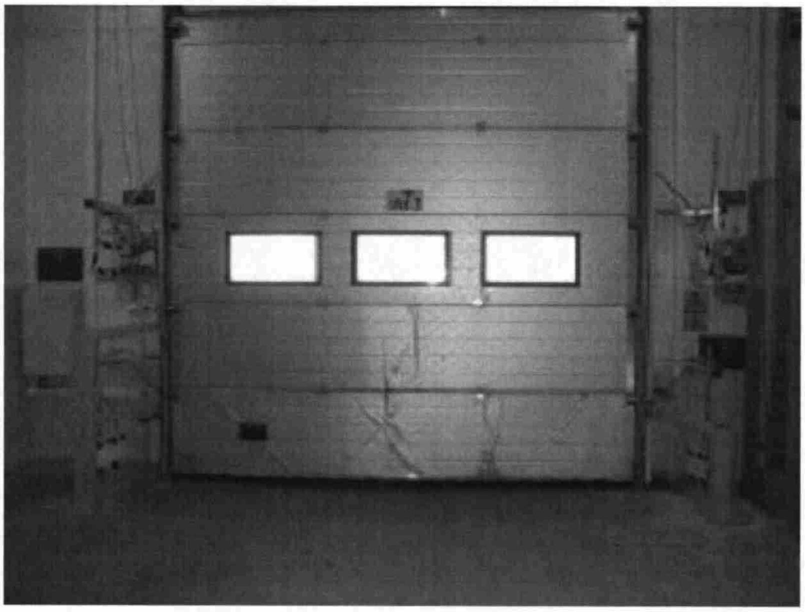


Figure 18. RFID equipped dock door at factory

RFID Gates are basically reader/antenna setups that are built to form a gate like structure that can be installed on dock doors for example, generally in places where tags are read by moving them through a RFID enabled gate. This is a very common way of building RFID systems, especially in logistics application where a lot of the tagged items are moved on pallets and dock doors are a natural point in the process where identification can be carried out.

Typical reading related difficulties at gates are fast movement speed through gate and having multiple gates close next to each other (multi reader environment), usually these can be solved with optimal reader settings according to [58]. This thesis aims to provide more information for solving these types of common issues.

2.10.2 Conveyor applications

Figure 19. RFID enabled conveyor belt

Conveyor belts are common in factories and they can also be equipped with RFID equipment. Typical for conveyor applications is relatively short reading range and a more controlled movement speed. Difficulties in conveyor applications usually are caused by the need for more accurate reading, continuous reading with fast moving conveyors and also achieving fast response times from the backend system.

2.10.3 Handhelds

Figure 20. Handheld RFID readers

RFID enabled handhelds are used in mobile applications, and in cases where fixed equipment is not possible to setup. Challenges with handhelds and real time operation come up usually with wireless communication to backend systems and slow speeds or connection problems. Special issues related to handheld applications are not in the scope of this thesis though, but the same Gen2 and RFID reading related issues apply also to handhelds.

2.10.4 RFID reader hardware

A reader (also called the interrogator in RFID systems) is the basic components in any RFID systems at the lowest level. A reader contains a RF module (transmitter receiver), a control unit and a coupling element to the transponder [18]. It communicates with passive transponders by sending energy, data and a clock signal.

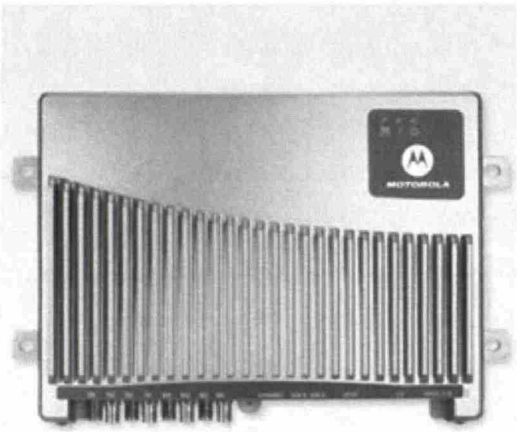


Figure 21. Motorola XR440 Fixed RFID Reader [34]

The range of readers on the market today is relatively wide, with several companies offering variety of hardware. Generally there are two main types of readers, handheld and portal readers. Handheld readers are smaller in size, portable and usually having a shorter reading distance. So called fixed / portal readers read from greater distance and they are usually mounted in a portal installation. They usually support multiple antennas, from 4 up to 8, and can cover a dock door for example with their reading area. Other differentiating factors are operating frequency (also high end multi frequency devices are available), read range and communication interfaces.

Figure 22. Nowadays UHF RFID readers are basically based on same type of design and for the standard type there are several vendor alternatives

The EPCglobal notes in [112] that different makes and models of readers may vary widely in the functionality they provide. On the market there are low cost readers available that do little more than report what tags are currently within the reader's RF field, and so called "smart" readers that provide sophisticated filtering, smoothing, reporting, and other functionality.

2.10.5 Reader communication interfaces and protocols

Typical physical interfaces for current RFID readers are Ethernet, serial and USB ports. Ethernet is widely used in fixed readers, because it allows them to be placed more freely in large systems and plugged directly into a company's network – not needing extra pc's or other hardware on its side. Managing and collecting data from several readers is convenient when the readers re in the same network. Readers equipped with serial ports or USB ports are usually intended for desktop use or as low cost standalone readers that have a pc nearby running the actual application. Often these readers have only one integrated antenna, but there are also exceptions. Many of the fixed readers at the market also have a serial port, but not usually only intended for maintenance tasks, such as changing IP addresses etc. when Ethernet configuration is needed.

Communication protocols used with readers from different manufacturers are not very well standardized yet. Most of the protocols used are manufacturer-specific. EPCglobal has recognized the need for standardization also in this aspect and they have developed two protocol standards, the "Reader Protocol 1.1" (RP1.1) and the "Low Level Reader Protocol" (LLRP) to be used with readers in order to harmonize the wide variety of custom protocols currently. However, currently most of the protocols used are still specific to manufacturer as can be seen from Table 5. Some of these custom protocols resemble actually the EPC standards (RP1.1 or LLRP), or are "inspired by RP1.1" for example, but compatible.

Reader	Communication port	Protocol
Motorola XR480	Ethernet	XML and Byte Stream
Impinj R1000	Ethernet	**LLRP**
FEIG LRMU2000	RS232, RS485 / RS422	FEIG ISO HOST
Thingmagic Mercury4	Ethernet	ThingMagic's Reader Query Language
Elektrobit URP1000	Ethernet	**RP 1.1 (certified)**

Table 5. Readers and their communication ports and protocols

2.10.6 Middleware

RFID middleware (commonly MW) is the layer of software that is needed in between the actual readers and the applications that take advantage of data provided by readers. It is not effective for enterprise applications to directly communicate with the RFID hardware and receive large amounts of raw data from them in return.

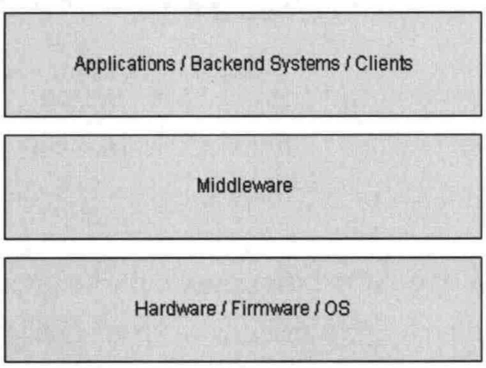


Figure 23. Definition of middleware

Basically in common RFID applications containing several readers and antennas a layer of RFID middleware is needed. RFID middleware takes care of tasks such as [p201-202, p252-253 13]:

- **Reader/reader network management** – Middleware is responsible of managing the actual device network, identifying readers and their locations, providing possibility to add/remove/change devices to the system, managing several types of hardware and communication protocols, etc.

- **Reader data collection** – Middleware provides implementations to reader data collection interfaces and handles the actual data collection process in an efficient and precise way.

- **Reader configuration –** Manual configuration of a wide device network can be difficult, but from a central location it can be done easily for whole network. Changes to reader configuration can be either parameter settings, power level adjustments, IP address changes and so on.

- **Diagnostics –** Middleware is also a convenient place for implementing monitoring status of devices in the network. Middleware may be able to send notifications, send alerts or provide diagnostics of devices to key users of the system [13].

- **Filtering of data –** Applying filter rules to the middleware layer prevents unnecessary data from reaching the backend systems. Unnecessary handling of large amounts of data is something that generally we want to avoid in ERP systems for example.

- **Data conversions from raw tag data** - RFID Systems generate large amounts of data from raw tag reads and they should be converted into meaningful events before forwarded into ERP systems.

- **Data storage, reporting of tag data**– Storage of tag data to a separate database can be done in the middleware layer, and reports of actual tag reads are usually needed for debugging problem situations.

- **Forwarding of data to other applications/backend systems, such as ERP** - RFID tag reads provide time, location and batch information that can be used to identify and locate specific products.

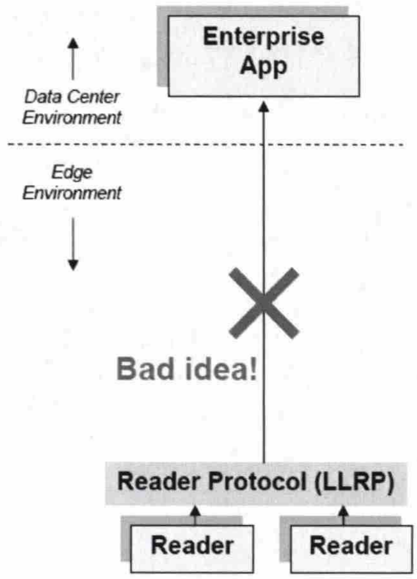


Figure 24.No middleware: Too much data, no local business logic, physical details not hidden from enterprise application, no real time capability [35]

EPCglobal has also developed a standard called The Application Level Events (ALE) Specification, specifying the middleware level interfaces for a system that is compliant with the EPCglobal Network Architecture. The role of the ALE interface is to provide independence between the infrastructure components that acquire the raw EPC data, the architectural component(s) that filter & count that data, and the applications that use the data [5].

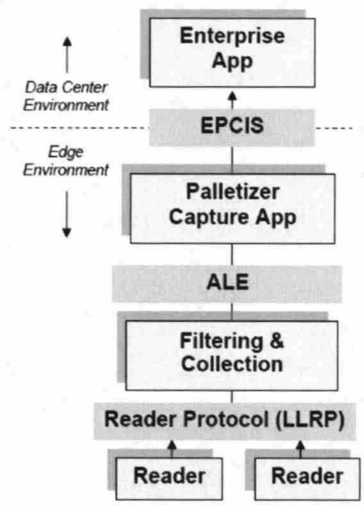


Figure 25. Middleware layers from viewpoint of EPCglobal Network Architecture [35]

The main goal of RFID middleware is to process real data, e.g. asset tracking events, from raw tag reads collected by the readers and hide the physical details of identification to the higher level systems [30].

3 INDUSTRY STANDARDS

Standardization of the RFID industry started in the late 1990's, when the lack of common standards was starting to affect the growth possibilities of the industry [2][8]. There were a number of efforts for standardization, but only two projects were successful in creating widely adopted standards: The ISO 18000 series and EPCglobal (formerly also called AUTO-ID Centre) specifications [8].

The ISO 18000 essentially specifies how an RFID system should communicate information between readers and tags (air interface standards) and the EPCglobal has a set of specifications on all aspects of operation of an RFID system from tag data content to system level architecture. Many RFID vendors have also their own standards that they have created for proprietary systems, but the EPCglobal standards and especially the widely spread Gen2 standard is the main focus of this thesis. Some other examples of ISO standardization for specific applications can be found in Table 2 and in Table 4.

3.1 Air Interface Standards

Air Interface standards specify the complete communication link between an interrogator and a tag including the physical layer, collision arbitration algorithm, command and response structure, and data-coding methodology [9]. The International Organization for Standardization (ISO) has standardized these air interfaces in the 18000 series of standards for most common RFID applications and frequency ranges that are used worldwide.

- ISO18000-1 Defines the foundation for all air interface definitions in the ISO/IEC 18000 series
- ISO/EN 18000-6 – Parameters for Air Interface Communications at 860 to 960 MHz

The 18000-6 standard details the parameters for how interrogators send and receive data from UHF tags. It also specifies the frequencies and channels to be used, as well as bandwidth, frequency-hopping and other technical details.

- ISO/EN 18000-6 Type C – Specifies EPC Class1 Gen 2

The EPCglobal Class 1 Generation 2 UHF Air Interface Protocol Standard was adopted in December 2004 and ratified as the ISO 18000-6 standard in 2006.

Interface	Level of communication	Standards:
Reader Protocol	Middleware / Reader communication	EPC RP1.1 / EPC LLRP / Proprietary protocols
Air Interface communication	Reader / Tag communication	EPC Gen2
		ISO 18000-6
RF Regulations and standards	UHF 860-960Mhz	ETSI EN 302-208 / FCC / Other regions

Table 6. Level of standards

3.1.1 Radio frequency regulations

RFID technology is subjected to directives and regulations generally concerning the use of bandwidth and the transmission output power on certain frequencies. Radio Communications agencies in every country or such institutions as ETSI (European Telecommunications

Standards Institute) in Europe and FCC (Federal Communications Commission) in the United States allocate the usage of spectrum and licenses. [21][31]

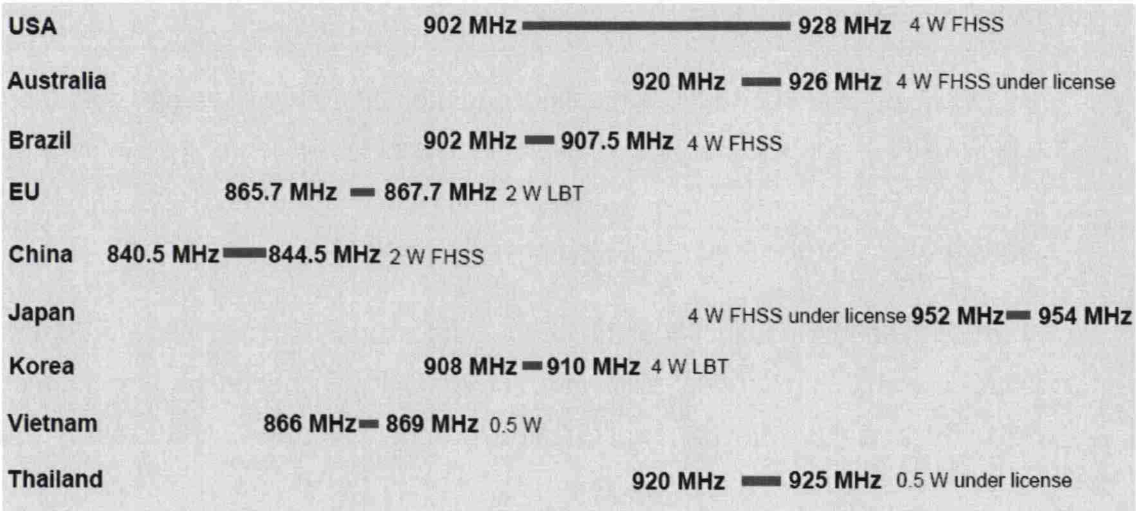


Figure 26. A Global Perspective on Frequency Regulation for UHF RFID [31]

Global functionality of Gen2 RFID tags require them to be designed to the UHF range of 860 - 960 MHz, covering all regulation regions, because each regulation area may have a different band designated for UHF RFID. This requirement is mostly taken care of by the tag manufacturers by optimizing their tag-antennas to a frequency somewhere in the middle of the UHF bandwidth (around 910 MHz) or by optimizing the performance for a certain region, so that tags will work globally, but with reduced performance [21].

Country	Frequencies (Mhz)	Power Level	Anticollision Technique
Europe	865.6-867.5	2W ERP	LBT
USA	902-920	4W EIRP	FHSS
India	865-867	4W ERP	FHSS
Japan	952-954, 952-955	4W EIRP	LBT

Table 7.Performance in different regions varies due to differences of regulations. [21]

In Europe the UHF RFID radio frequency spectrum is governed by ETSI and the regulations are stated in the ETSI EN 302 208-1 standard. It defines technical requirements and methods of measurement, Electromagnetic compatibility and Radio spectrum Matters (ERM) for Radio Frequency Identification Equipment operating in the band 865 MHz to 868 MHz with power levels up to 2W [22].

3.1.2 ETSI EN 302-208-1

The ETSI EN 302 208 regulation defines the regulated bandwidth and output power of UHF RFID range products, and also prescribes the division of the bandwidth in channels, the communication technique for the reader, maximum time per transmission and the reader-antenna beam width [21][22].

The ETSI standard defines that the frequencies used in for UHF RFID in Europe shall be from 865.0 to 868.0 MHz and is divided into 15 channels with a width of 200 kHz. The maximum output power is 2 W ERP, but not for all 15 channels. [21][22].

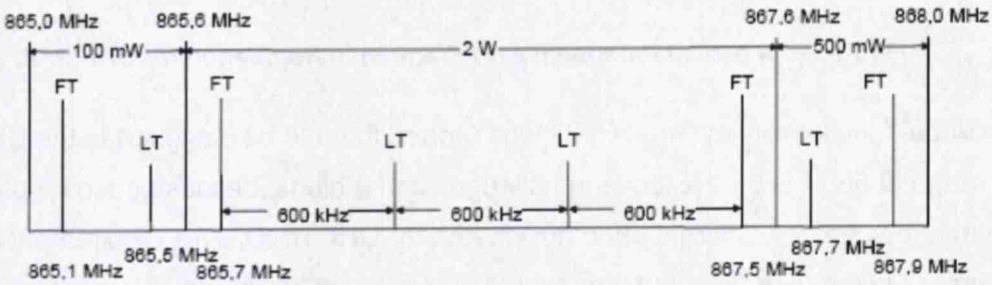


Table 8. Division of the European frequency bands [22]

Power class	Frequency band	Power level
11	865,0Mhz to 868,0Mhz	+20dBm
12	865,6Mhz to 868Mhz	+27dBm
13	865,5Mhz to 867,6Mhz	+33dBm

Table 9.Allowed power levels in different bands in Europe [22]

Power levels can be converted from dBm to Watts using the equation:

$$mW = 10^{\frac{dBm}{10}}$$

According to this conversion 33dBm corresponds to about 2W, 27dBm is about 500mW and 20dBm is 100mW. Usually output power of the reader is given in Watt

ERP. ERP stands for Effective Radiated Power and is the power radiated by the antenna of the reader in its direction of maximum gain [21].

The ETSI regulations also prescribe a reader-to-reader anti-collision method, that must be implemented by the readers. This technique is used to determine an unoccupied channel in order to minimize interference with other users on that same channel. For ETSI region this agile technique is so-called Listen- Before-Talk technique or LBT in short. In LBT technique the readers are required to listen a channel before they are allowed to transmit, and they can only transmit if the noise level measured by the reader is lower than the required limits.

Transmit power	Threshold
Up to 100mW	≤-83dBm
101mW to 500mW	≤-90dBm
501mW to 2W	≤-95dBm

Table 10. LBT Threshold levels [21]

The ETSI standard and LBT rules require that before each transmission the reader must listen for 5 milliseconds to the channel it is about to transmit and if the detected level is above limits (example shown in Table 10) the reader must not transmit on that specific channel. Reader then changes to another channel and listens to that first, before transmitting. Also the reader is not allowed to occupy a single channel for more than 4 seconds at maximum, after which it has to switch channel or wait 100 milliseconds idle. Each channel switch must of course start wit a listen period [21]. The LBT rule creates a small effect on the real time performance of reading fast moving tag: a periodical 5ms wait time have to be added to the calculations when estimating read cycle lengths.

ETSI regulations also are limiting the beam widths of antennas used in RFID systems. According to the standards horizontal and vertical orientations shall not exceed 70 degrees for transmissions over 0.5W and 90 degrees for transmissions under 0.5W [22]. This somewhat limits the possibilities to cover larger areas for reading, but also limits emitting RF noise to the surrounding environment. In ETSI region it is considered a good practice to avoid unnecessary RF emissions, and equipping readers with sensors for example is a good way to limit the time a reader is occupying RF band [22].

3.1.3 FCC regulations

In the United States FCC is the organization that is governing the regulations concerning UHF RFID radio spectrum. There are some differences in comparison to ETSI standards that are also affecting the performance and operation of RFID devices.

One of the major differences is the bandwidth available in the FCC region: 26 MHz, which is divided into 50 channels. Each channel having wider area (500 kHz) than in ETSI (200 kHz) regulations. The larger bandwidth enables better performance in dense reader environments where many readers are operating at the same time. According to [21] the chance of having reader-to-reader collision in Europe is 5 times higher than the chance of having these collisions in the US.

Instead of using LBT, Listen-Before-Talk, technique for avoiding reader-to-reader collisions, the FCC systems use technique called “Frequency Hopping Spread Spectrum” (FHSS), which is a transmission technology where readers change from channel to channel in a pre- assigned, pseudo-random sequence. A reader is allowed to transmit for a maximum of 0.4 seconds before it has to 'hop' to another channel. FHSS eliminates the need for a listen period that would be pausing the tag inventory cycle and thus allows a duty cycle of 100% [21].

Noticeable is also the fact that FCC allows using higher power levels than for example in ETSI region, FCC allows 4W EIRP (2.44 W ERP) when ETSI standard limits power to 2W ERP. This in turn increases performance of the system as tags respond better.

3.1.4 Future developments of ETSI standards

The current ETSI standard (V1.1.1) is based on the work started in 2002 and the needs at that time. For example planning for standard was done according to hardware available then and expecting that individual sites would have less than 30 readers or so, which was the estimate at the time. So the standard was designed to use 10 channels and relying on LBT to solve interference problems. However the market has grown since then, and currently the need would be for much larger installations with as much as 200 readers estimated at maximum per site. Also the capabilities of current technology are better. Narrow bandwidth for UHF RFID in Europe causes problems with interference between RFID readers in sites with multiple readers. The interference problems in Europe are bigger than in regions that have a wide frequency range such as FCC region. [39][21] Also according to [21] using LBT as the technique for frequency use causes problems when 5 or more readers are operating in the same general area.

A new version of ETSI standard 302-208 has been published in April 2008 that brings several improvements to the previous standard. Improvements mainly include:

- Better operation in dense reader mode with 4-channel plan
- No LBT
- New concept, tag presence sensing

The V1.2.1 of ETSI 302-208 defines a so called "4 channel plan". It says that an interrogator may transmit on any of the 4 high power channels and tags respond in the adjacent low power channels. Splitting the channels for readers and tags separately result in the fact that readers will collide with other readers but not with tags. Current readers on the market are able to filter interfering readers from their tag responses, allowing multiple interrogators to share the same channel thereby improving system performance. New version of standard also removes the mandatory requirement for LBT, since the readers are able to share channels. [39][21][22]

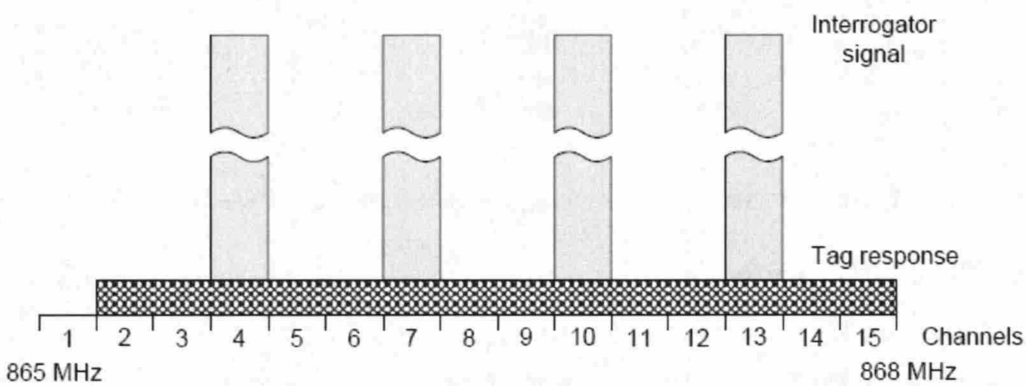


Figure 27 4 Channel Plan [22]

The tag presence sensing means that now interrogators may also operate in a "presence sensing mode" in which they periodically transmit to determine whether tags have entered their interrogation zones while not committing an actual inventory or read cycle. [22]

So other minor changes consider antennas: there is no restriction on antenna beam width below 500 mW ERP. [39]

The version 1.2.1 of ETSI 302-208 is currently published but not yet ratified for use in most countries.

Quick growth in the RFID business and development of technology has already started to create need for even further development of the ETSI standard for UHF RFID. Next steps for development according to ETSI [39] are:

- Global harmonization
- Large number of different applications
- Need for higher data rates and more power
- Increased functionality (e.g. sensor tags)

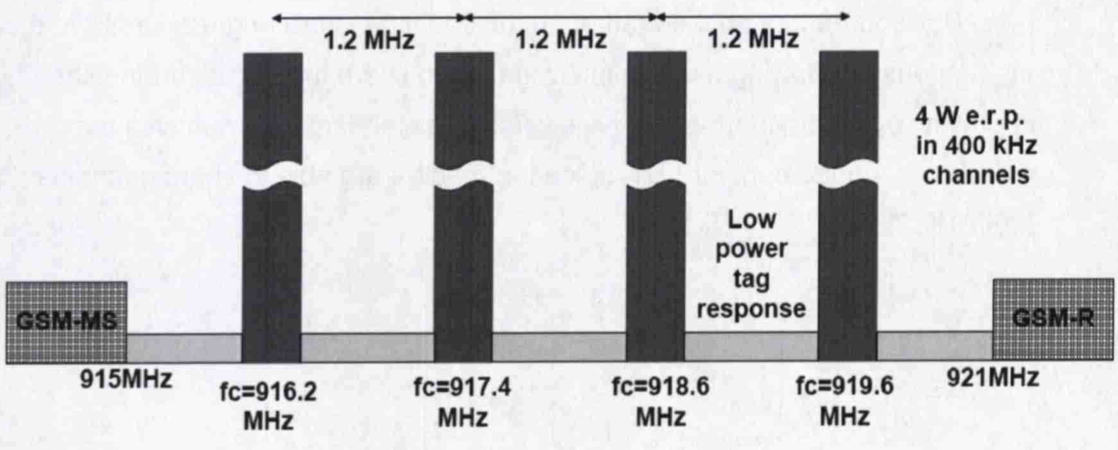


Figure 28 Proposal for new frequency range in ETSI region [39]

The drive of ETSI standards seems to be going towards global standards. For example ETSI suggests that in future 915 to 921 MHz band would be used also in Europe for UHF RFID. They are also planning improved performance with greater read ranges, better penetration inside pallets (etc) to read tags, faster data rates

(320 kb/s vs. 80 kb/s) and increased functionality (tags with sensors). Their estimate is that the new version of the standard will meet market needs in Europe only for next 5 years. [39]

3.2 Electronic Product Code and EPCglobal standards

The Electronic Product Code (EPC) is an identification scheme for universally identifying physical objects via RFID [41]. Basically it is just a numbering or a key that links a tagged item (unique id), such as a pallet, to detailed information in a backend system. The EPC system defines technical protocols and data structures for the stored information. Based on the UPC codes from EAN.UCC type bar coding the EPC code is used similarly for RFID tags [13]. EPC coding standards are managed by EPCglobal Inc - a joint-venture between GS1 and GS1 US. GS1 administers the UPC bar code system [13].

EPCglobal is the commercial successor of Auto-ID Center, which is the original creator of EPC (formerly Auto-ID) standards and specifications. Auto-ID Center was formed in October 1999 in MIT [13]. It was one of the organizations that recognized a major problem in the early RFID technology: Lack of standards as vendors on the market were offering only proprietary systems. Auto-ID Center started to develop a single open standard in a research program focusing on creating an interoperable environment with regulatory compliance and increased performance for RFID systems [40]. The standards of Auto-ID Center were the base to the currently widely adopted EPCglobal standards.

The Auto-ID Center itself ended its work in 2003, licensing its research results to the EPCglobal Inc. [40]. Auto-ID Labs is a network of academic research labs that currently continues to research and development work of the Auto-Id Center in cooperation with EPCglobal. [40] [13]

3.3 Class-1 Generation-2 UHF RFID standard

The Auto-ID Center's aim of the next generation standard, based on UHF RFID, was intended for simple and inexpensive RFID tags and to be implemented in supply chain and store management processes. Developing a low cost RFID solution was the key: Reducing the chip price on a tag was one way of achieving that. Amount of silicon required in RFID chip was minimized, which in turn required the reduction of the information stored on chip to a serial number or ID only (EPC code). All other product information was to be held on a networked database [8]. Because many Gen2 systems rely heavily on the EPC coding and backend systems, EPCglobal has also published many standards on those areas.

The research program proposed standard specifications for the Generation 2 tag/reader systems and it was published in 2003 by Auto-ID Center [19]. EPCglobal was formed to take care of the commercialization of the Auto-ID standards and it became ratified as "Generation 2 UHF RFID Protocol for Communications at 860 MHz - 960 MHz" or simply "Gen2" in short [13].

Key features of Gen2 standard and improvements in comparison to other RFID standards:

- Global, open, interoperable standard
- Low cost of tags
- Efficient and accurate tag population management
- Robust air interface (signaling) protocol
- Dense reader operation
- Security features, including "kill" capability
- Fast read rates

[13]

Gen2 was designed to be a global protocol. The tag specification is global and allows identification of same Gen2 tags on any regions as they are shipped with goods all over the world. However, as there are regional differences in frequencies, admitted power levels, and so on (see section 3.1.1), Gen2 is based on locally varying hardware, which is one of the biggest arguments for critics of Gen2 systems.

3.3.1 Air Interface

In Gen2 protocol the readers transmit data to tags by modulating the RF signal (carrier signal), that they send. Passive tags that are within the signal field receive energy from that signal and also receive data according to the modulation. Readers receive information from tags by backscatter transmission (described in section 2.8.2) when they respond by modulating the reflection of carrier wave. This is done by changing the impedance state of the tag antenna. The communication between readers and tags is completely directed by the reader, and thus the technique is called "Interrogator Talk First" (ITF). The communications are half-duplex, meaning that readers talk and tags listen, or the other way around. [9]

Reader to tag communication link is based on using double-sideband amplitude shift keying (DSB-ASK), single-sideband amplitude shift keying (SSB-ASK) or phase-reversal amplitude shift keying (PR-ASK) using a pulse-interval encoding (PIE) format. Tag to reader communication link is based on amplitude or phase modulation of the RF carrier. The encoding format of the tag to reader communication link can be selected by reader commands; it is either FM0 or Miller-modulated sub carrier. This means that the communication links can be configured according to the RF environment, increasing performance in different environments [9]. To be able to take advantage if the features all Gen2 tags must implement FMO and Miller modulations. Gen2 compliant readers on the other hand need not implement all cases. [42]

FMO encoding is the simplest, and it has data rates from 40 kbps to 640 kbps. FM0 has the best sensitivity, fastest data rate, and it is good for easy RF environments.

Miller-modulated sub carrier (MMS) is a more elaborate encoding. There are 3 different MMS schemes are available, Miller-2, Miller-4 and Miller-8. Miller encodings are more robust on RF, have lower sensitivity, but also lower data rates. For example, using the slowest BLF (Backscatter Link Frequency, which specifies the pulse width of the shortest tag to reader link feature) of 40 kHz, the data rate for Miller-8 is the BLF/8 = 5 kbps. To transmit a 96-bit EPC and 16-bit error check will take 22.4mS, corresponding to less than 45 tag reads per second for Miller-8. [42]

The ability to vary both the backscatter link frequency and the data encoding (FM0 or an MMS) allows the user to optimize the tradeoffs of tag data rate, read range, interference tolerance and multiple reader operation [42].

Table 11 Effect of different encodings on data rate [42]

BLF (kHz)	Encoding	Data Rate (kbps)
40	FM0	40
40	Miller-2	20
40	Miller-4	10
40	Miller-8	5
256	FM0	256
256	Miller-2	128
256	Miller-4	64
256	Miller-8	32
640	FM0	640
640	Miller-2	320
640	Miller-4	160
640	Miller-8	80

In the Gen2 specification the length of zero bit of communication can be altered also according to the RF environment. The '0' symbol duration is denoted as "Type A Reference Interval"(TARI). It is a simple pulse, with a 'low' time of 1/2*TARI, and a 'high' time of 1/2*TARI. The '1' symbol duration can be between 1.5*TARI and 2*TARI, with a 'low' time of 1/2*TARI. Setting a long TARI improves readability in noisy environments and setting a short TARI improves data rates. [42]

Table 12 TARI effect on data rates [54]

TARI (μs)	Data rate (kbps)
6,25	107-128
12,5	53,3-64
25	27-32

3.3.2 Tag population management

In many applications there are multiple tags simultaneously in the field of view of a reader and readable. Basically this corresponds to a common situation any telecommunication systems where multiple users share a common medium, in case of RFID, the common medium being the frequency band used by reader and the tags in RF field. Several techniques and protocols have been developed, especially for telecommunications, for shared medium for transmissions or medium access control (MAC), such as: CSMA/CD (used in Ethernet and IEEE 802.3), CSMA/CA (used in IEEE 802.11/WiFi WLANs), Slotted ALOHA, Dynamic TDMA, Reservation ALOHA, CDMA and OFDMA. [44]

In previous Class 0 and Class 1 systems the communications is handled by using a binary-tree approach, in which there is a unique identifier (Tag ID) assigned to each tag and the reader goes through numbers from the tree, until it is talking to just a single tag. The reader then retreats up the tree and tries to "singulate" another tag. This process repeats until there are no more tags left responding. Binary-tree protocols are according to [42] exhaustive. This kind of population management should find all tags present in the field, but is slow and due to momentary signal fades tags can sometimes miss their singulation slot or talk at the wrong time. [42]

The Gen 2 standard uses a technique based on the ALOHA protocol. In generating an inventory Gen2 uses a so called slotted Aloha protocol [42]. In ALOHA system (many current communication protocols are based on ALOHA, such as Ethernet [45]), all nodes (tags in this case) communicate on the same frequency. This means that some sort of system is needed to control who can talk at what time. The Aloha protocol was one of the first attempts to allocate a wireless medium in a non-deterministic fashion [42]. The basic principle of ALOHA is that in case transmission error due to interference / collided message the sender waits for a random length of time and tries resending after that [43]. The slotted Aloha protocol divides the transmission time into specific time slots and each sender randomly chooses a time slot in which to transmit and if there is a transmission error the sender just chooses a new random slot for resending [42].

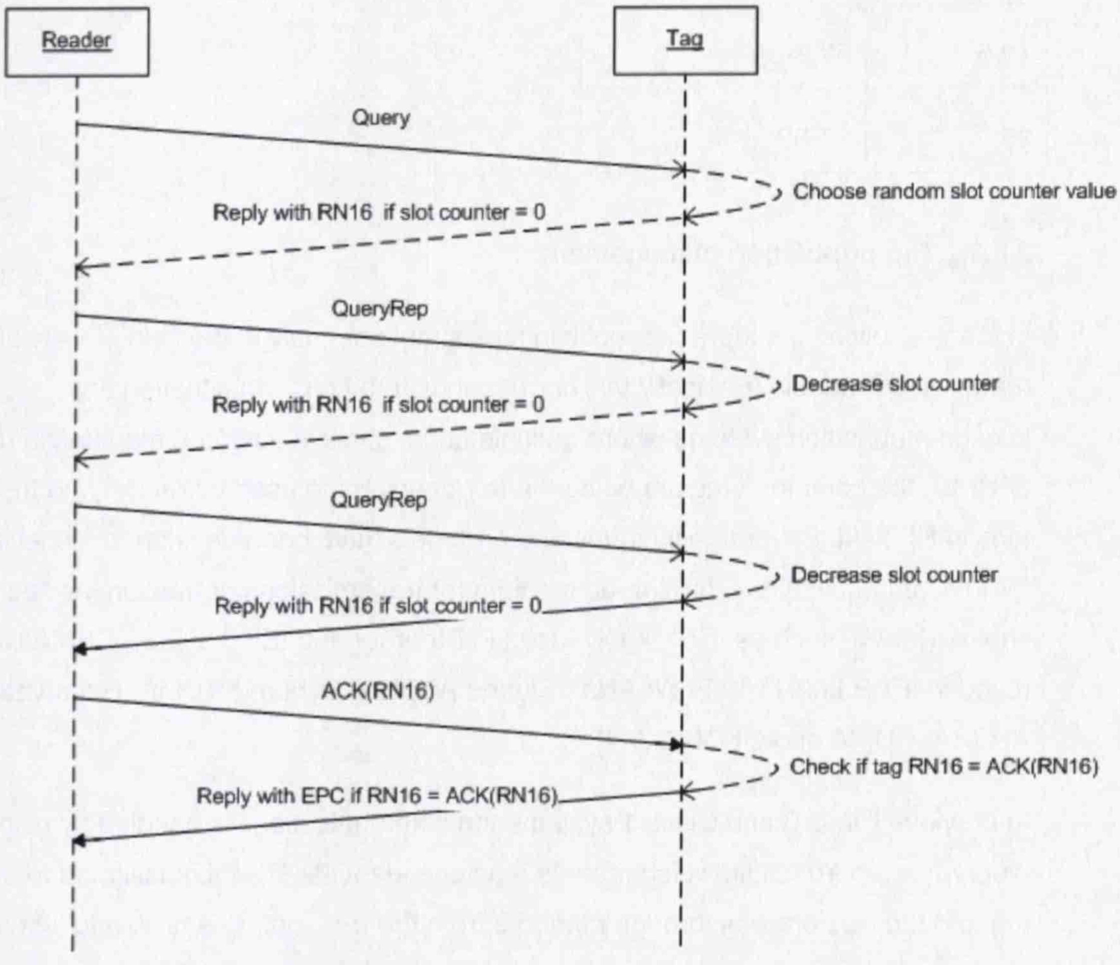


Figure 29. Inventory process

The slotted ALOHA protocol in Gen2 is called sometimes the Q-protocol (after Q parameter it is based on). Q algorithm allows singulation of tags, even if they have the same ID [42] [46]. Basically the Q value determines amount of transmission slots in the protocol – number (n) of slots can be calculated according to $n = 2^Q$. [9]

When the reader start to inventory tags in its range, it starts by announcing the Q value. Tags then pick up a random value to their slot counters from range 0 to 2^Q-1. Any tag with a slot counter value 0 sends a reply. All other tags decrease their slot counter by 1 according to reader commands until they reach 0 and reply. Reader commands tags to decrease slot counters until it reaches all 2^Q slots. Inventory is based on a random protocol, but the Q-parameter makes it possible for reader to regulate probability of tag responses. Q is an integer in the range of 0-15, which means that corresponding probabilities for tag replies are from 1 (Q=0) to 2^{-15}. By changing Q the reader can adapt to the number of tags present. Each round of the Q-protocol is not guaranteed to see every tag in the field, but if the reader detects collisions it can increase Q-value for next round and if there are lots of empty slots the reader can lower Q value for better inventory rates. The starting value for Q is normally a key parameter that a user has to set for the reader. [9] [42]

Sessions are a feature of Gen2 that allows several readers to communicate with (inventory simultaneously) the same set of tags. It I also a way of making tags quiet for a moment after inventory. This helps in inventorying large tag populations.

There are four sessions for each tag, basically four unique flags that tags maintain: S0, S1, S2 and S3. They can each be of value A or B and tags maintain each flag value independently. In the beginning of an inventory round the reader chooses a session and if it is inventorying A or B tags. A reader can set the flag for a tag from A to or B to A after singulation. Different readers inventorying same tags must be using different session and when they do two inventory rounds (from A to B and B to A) all tags will be inventoried in the field. Because the session flags have different persistence properties, this parameter can also be used to help inventorying large populations. S0 tags will answer always for each inventory round – this makes it suitable when fast reading of small amount of tags is needed. S1, S2 and S3 tags have longer persistence times (up to seconds) and that help inventorying large populations, when a part of tags are quiet during rounds. [9][46] [42]

S0: Tag responds always
S1: Tag quiet between 0.5 and 2s
S2: Tag quiet above 2s (typically e.g. 5s)
S3: Tag quiet above 2s (typically e.g. 30s)

Table 13. Session persistence times [9]

3.3.3 Tag memory

Gen2 specifies that the memory of the tags must be organized into 4 memory banks: Reserved, EPC, TID, and User. TID contains a manufacturer hard coded Tag id (information about tag properties not necessarily a unique serial number), EPC contains the actual EPC code (length may vary, PC bits describe length), Reserved contains passwords etc. and User block may contain space for user specific data. Readers can lock, unlock or permanently lock/unlock tag memory banks, but the TID, EPC and User banks are always readable. [9]

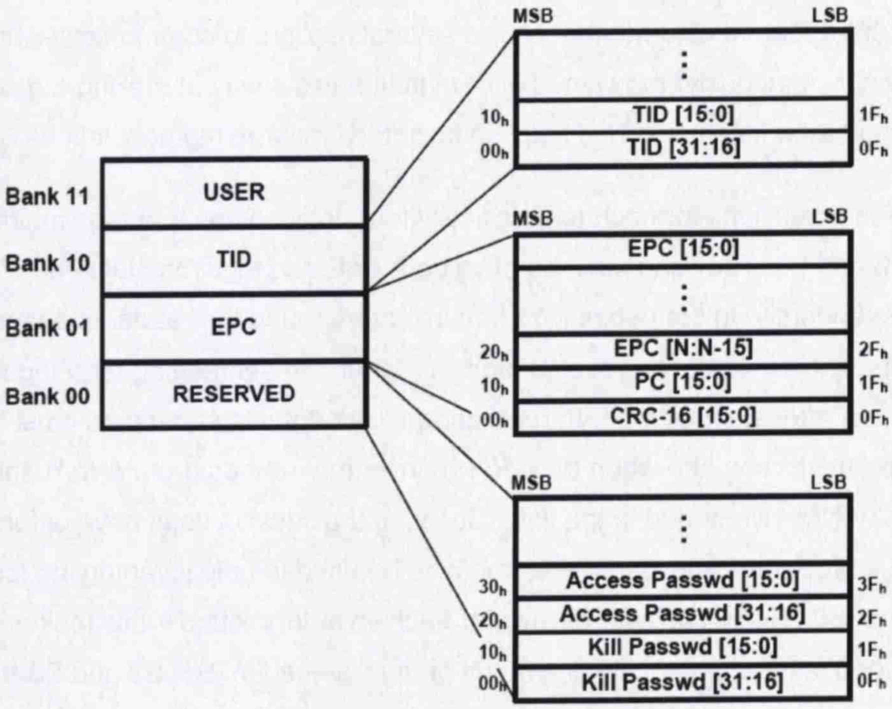


Figure 30. Gen2 tag memory contents [9]

3.3.4 Reader commands

The Gen2 specification defines four command types for readers: Mandatory commands – all compliant readers and tags must support these commands, optional commands that readers or tags may implement, proprietary commands that can be used for manufacturing purposes (disabled after manufacturing) and custom commands that may be implemented to enable additional features. [9]

Type	Command	Implementation
Select	Select	Mandatory
Inventory	Query	Mandatory
Inventory	QueryRep	Mandatory
Inventory	QueryAdjust	Mandatory
Inventory	ACK	Mandatory
Inventory	NAK	Mandatory
Access	Req_RN	Mandatory
Access	Read	Mandatory
Access	Write	Mandatory
Access	Kill	Mandatory
Access	Lock	Mandatory
Access	Access	Optional
Access	BlockWrite	Optional
Access	BlockErease	Optional

Figure 31 Commands for basic operations

The readers use these commands to manage tag populations. Basically the communication is based on three basic operations: Select, inventory and access.

Figure 32. Three basic operation sets a reader can use

Select is process that the reader uses to select a particular group of tags (population). Tag population can be selected according to user defined rules, such as a union, negation or intersection of certain tags. This allows the further commands (inventory, access) to be executed only on the population of tags that is needed. Extracting unwanted tags form the inventory process for example prevents collisions and shortens the inventory round. [9]

Select command parameters specify: Session, inventoried flag (A/B), bit mask for a certain memory bank and also the length of EPC code that the reader wants tags to backscatter. Multiple select commands can be issued before inventory. [9]

Inventory command set is used to determine which tags are currently in the field of view of the reader. These commands control the inventory rounds and Q-protocol described in 3.3.2. Query is the command that starts an inventory round; it sets the starting Q-value and specifies the air interface parameters (see 3.3.1) such as tag to reader link frequencies to be used, data rates and modulation formats. Query also contains parameters for selecting session, flag (A/B) value etc. QueryRep is used by the reader uses to decrease tags' slot counter. QueryAdjust adjusts the Q-value. ACK and NAK are used to reply to the tag's backscattered response. [9]

Access commands are used to read and write tag's memory banks or kill/lock/unlock it. Before access commands can be used a tag must be uniquely identified and all of the access commands actually contain the tag's unique "handle" value as a parameter. Access commands must be started by solving the handle value with Req_RN command; this insures that only a single tag is modified. Kill is a special command in Gen2, it permanently disables the tag and it can only be issued after a multi step procedure, where the reader needs to know the passwords for example (not possible accidentally). Lock commands can be used to lock memory bank data, either permanently of with password. Unlock naturally unlocks memory bank data, permanently unlocking is also possible. [9]

3.3.5 Dense reader operation

Gen2 was initially designed for Logistics applications. One common Gen2 application is to detect moving objects at dock doors in Warehouses or distribution centers (DC). DCs have usually multiple dock doors and material flows constantly through many doors at the same time. These kinds of applications require readers to be placed close to each other and they also need to be reading at the same time.

With large scale RFID systems, one of the common problems that emerge is the reader collision problem [47]. Reader collision problems mainly occur where several readers try to interrogate tags at the same time in same vicinity.

So called “reader to tag” collisions occurs when the signal from a neighboring reader interferes with tag responses being received at another reader. This is caused by the fact that in terms of RF power the signal transmitted by the readers is much greater than a backscattered response of tags. This means that a reader can be quite far away and still be able to interfere with tags. According to [47] it was discovered that, if a tag is located 10 meters away from an interrogating reader, then the antenna of the other readers must be around 2865m away (same power level measured for transmissions by tag backscatter and other reader’s signal at the interrogating reader, calculated from free space path loss).

The Gen2 specification provides a solution to this problem with a technique called “Dense Interrogator Mode” or “Dense Reader Mode”. In dense reader mode the readers must use either Time Division Multiplexing (TDM) or Frequency Division Multiplexing (FDM) methods depending on the regulatory region that they are operating in [9]. In TDM the readers are synchronized temporally and send their commands at the same time and listen for tag responses at the same time. FDM method isolates the readers and tags to different frequencies. Readers will be only colliding with other readers, but not with tags. Readers that support the dense reader mode must be certified by EPCglobal. [9]

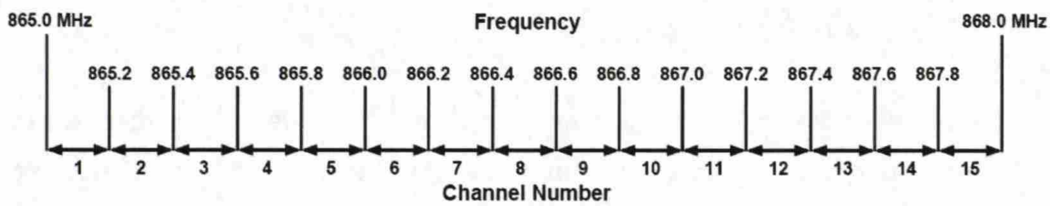


Figure 33 Channels of ETSI region [9]

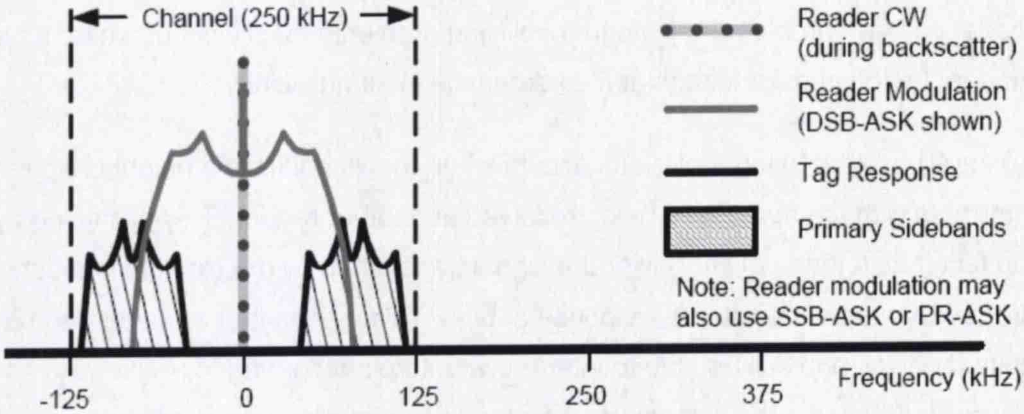


Figure 34. TDM Example [9]

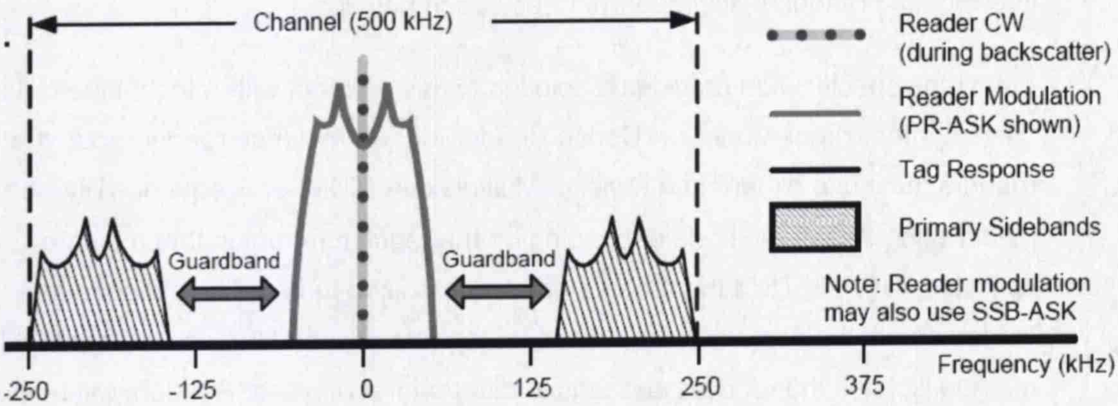


Figure 35. FDM Example [13]

3.4 Network architecture

EPCglobal Network Architecture is a set of specifications (hardware, software and data standards) for reading and managing EPC objects. It defines standard open interfaces and definitions of components that users can implement or acquire from vendors in order to create RFID systems that are interoperable with other implementers of EPC Network and EPC data. It shows how implementers can deploy systems conforming to EPC Network. Architecture Framework shows how all the interfaces and components fit into one larger picture. [2]

In addition, it defines the high-level architecture of the core services operated by EPCglobal and its delegates. One of the document's goals is to provide architectural guidance to technology vendors (and end users) implementing EPCglobal standards and to end users deploying systems conforming to EPCglobal standards and utilizing EPCglobal Core Services.

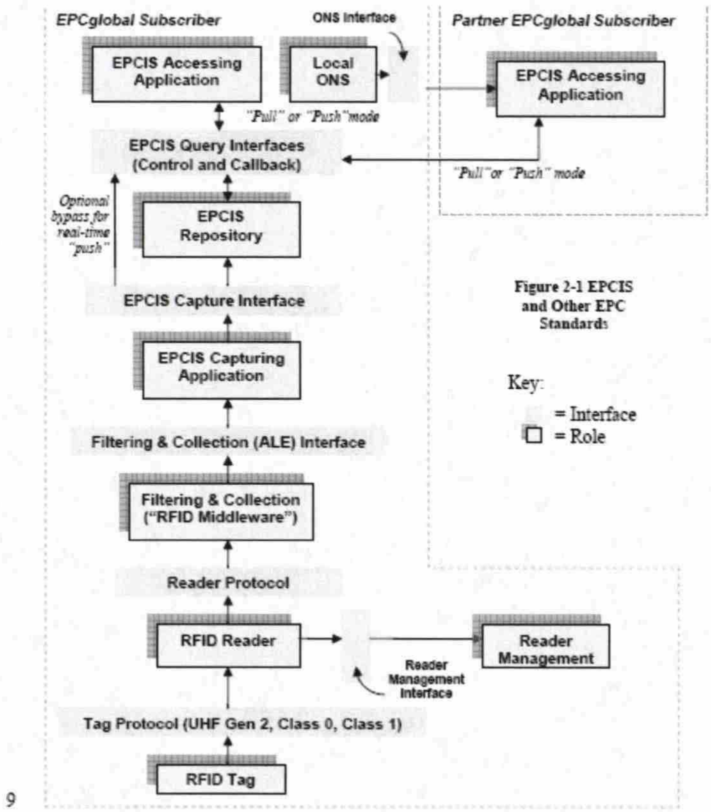


Figure 36 EPCglobal Architecture Framework [2]

3.5 Reader protocol standard

The Reader Protocol (RP) standard is an attempt to unify the interfaces between (Gen2) RFID readers and controlling applications. Currently most of the readers do not support Reader Protocol, as can be seen from Table 5. Readers and their communication ports and protocols), but it has served as a base for the design of many proprietary reader interfaces. Many of these proprietary interfaces have similar functions and capabilities.

The reader Protocol defines three layers: Reader layer, messaging layer and transport layer [112].

Asynchronous systems are generally more efficient on performance compared to polled systems, due to following advantages:

- Avoids unnecessary polling when nothing to report – less data traffic and lower capacity needs for IT systems
- Faster response times due to immediate notifications – no need to wait for next polling cycle
- Autonomously operating readers – simplifies controlling application implementations
- Smart gates can generate notifications only from meaningful events– simplifies controlling application implementations

Te main disadvantages of RP are:

- Heavy configuration of readers (many readers if in network) needed (event generation, reporting, air interface settings)
- Problem situations difficult to recognize

3.6 Low level reader protocol

For some application the Reader Protocol was too high level in its functions. The design of the Low Level Reader Protocol (LLRP) interface recognizes that in some RFID systems, there is a requirement for explicit knowledge of RFID air protocols and the ability to control Readers that implement RFID air protocol communications [48].

LLRP provides capability for the applications to control readers according to the lower level commands. Using LLRP applications can command readers to commit inventory rounds, read and write operations, kill and lock commands directly. It also provides means to control even air interface parameters included in the commands, such as forward and reverse RF link operation. With LLRP being able to use air interface parameters there is a possibility for client applications to manage reader-to-tag and reader-to-reader interference situations and maximize the efficiency of singulation and data operations. [48]

The benefits of LLRP are:

- Low level control – good for difficult applications and RF environments
- Light configuration needed for readers
- Open toolkit available – many vendors seem to favor this interface and support it in the future [49]

3.7 Application level events interface

The EPC Application Level Events (ALE) interface tries to create a standard way for gathering data from middleware level. In the framework application business logic (or EPCIS) is the top level component using ALE interface provided by middleware (filtering & collection level). Large amounts of EPC data should translate into meaningful events in the ALE level interface.

The ALE interface is oriented towards real-time processing of EPC data, with no persistent storage of EPC data (not required by the interface). Historic data and persistent storage is assigned to higher level components. The interface provides means for business applications to specify, in high-level, what data they are interested in or what operations they want performed, without dictating an implementation. It also creates a new abstraction layer between actual readers and the business applications. Components using ALE subscribe to events from "logical readers" (often synonymous with location) hiding from clients the details of exactly what physical devices were used. This making changes to the physical layer (for example, replacing reader at a loading dock door) without affecting client applications. [5].

The events communicated through the ALE interface are pure statements of "what, where, and when," with no business semantics expressed. Business applications can then translate these events to business transactions for example. The ALE description [5] gives us a good example about the semantics: At the ALE level, there might be an event that says "at location L, in the time interval T1–T2, the following 100 case-level EPCs and one pallet-level EPC were read." Within a business application, the corresponding statement might be "at location L, at time T2, it was confirmed that the following 100 cases were aggregated onto the following pallet." [5].

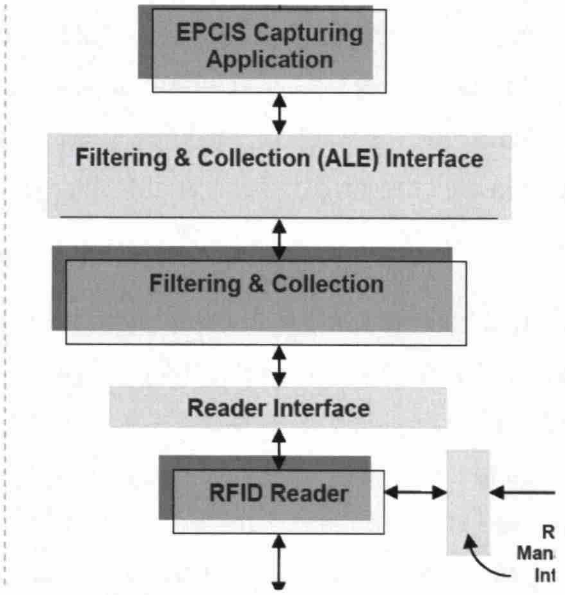


Figure 38. Notice the arrows pointing in both directions - return channel also included in ALE level [5]

Noticeable is that ALE level currently (version 1.1) also specifies a so called "Writing API" that can be used to send return channel commands back to readers, such as tag writing, kill events, operating printers, etc. Lack of the return channel used to be one of the main questions previous of ALE 1.0 in terms of applying ALE to real time applications requiring actions or commands to be sent back to the lower level devices.

3.8 Security

According to some studies RFID technology poses several security and privacy threats [63]. Mostly the security issues and arguments concern privacy related threats and are based on the basic nature of Gen2 tags – reading of the EPC code is possible by any reader and one could identify the object associated with the tag. Duplicating a similar tag and EPC code is also simple and may pose a threat to a user of the technology. [50]

In the paper of [51] several threat models are introduced concerning RFID systems, such as: Spoofing identity. An attacker could for example duplicate a tag and let himself inside a RFID system. Tampering with data. An attacker could modify, add, delete, or reorder data on tags. Information disclosure. Information is exposed to an unauthorized user. Denial of service. Denies service to valid users. According to [51] Denial-of-service attacks are easy to accomplish and difficult to guard against in Gen2 systems. [51]

One example of a possible security problem with Gen2 systems could be that an attacker kills tags that are moving in the supply chain disrupting business operations and causing a loss of revenue [51]. Of course same kind of harm could be done to barcodes, if an attacker has access to the tags or labels. Similarly a thief could destroy tags to remove merchandise without detection from a store that uses Gen2 tags as anti-theft system. A denial of service attack could also be a possible threat; An attacker with powerful reader is able to jam reading by creating a more powerful return signal than the signal returned from the tags, taking advantage of the reader collision problem and thus making the system unavailable to real users. [51]

4 RESEARCH PROBLEMS

Real-time availability of RFID data is critical for many RFID applications, such as manufacturing automation systems, process control systems, advanced materials handling systems and supply chains [53]. RFID applications in these areas will usually require real-time data to make control decisions, and will then execute the decisions in real-time to control the physical process flow, in order to meet certain hard timing constraints. [52]

Reliability and the ability to carry out operations within time-constrains are two main factors in real time systems. Thus far only a little has been published about the use of RFID in the real-time domain [52]. The aim of this thesis is to study the capabilities of current Gen2 technology from real-time perspective. This section of the thesis introduces some problems that have been faced with Gen2 systems and describes some solution possibilities to these problems.

4.1 Real time systems

Real-time refers to operational deadlines from event to system response. In a real-time system, the correctness of an operation depends not only from logical result but also from the time in which it was produced, a deadline. According to [*54*] the classical way of classifying real-time systems is to divide them according to the deadline into two types: Deadlines can be either "hard" or "soft. In a hard or immediate real-time system, a catastrophe could result if a deadline is missed (e.g. stopping a train in traffic). For a soft real-time system it is permissible to miss the deadline occasionally, it will tolerate lateness, and may respond with decreased service quality (e.g., dropping frames while displaying a video). [54]

The term real-time mentioned many times in RFID systems is actually meant mostly only as timely or fast, and does not refer to meeting individual task timing constraints [*52*].

In RFID Systems, a main issue for machine-to-machine communication is that the flow of information differs substantially from that in present-day computer networks. Instead of a large flow from central servers to clients at the edge of the network, the main data flow for RFID and sensor network systems is from many devices at the edge of the network towards a few central servers [4]. In both, control systems and in RFID systems, sensors or RFID readers detect certain events and forward the information to business applications on central servers or automation system controllers. Servers and controllers respond to the inputs and issue actions according to the situation. To enable fast response times in such a system, a part of the business logic may have to be also distributed closer to the edges of the network (such as filtering, collection and control of subsystems). Decisions made on a central server usually take longer time than is acceptable in many cases where fast response is needed. If the central server is located in a remote destination, it may be impossible to guarantee any kind of response time (communication over internet). EPC ALE level (filtering and collection component) software is a part of this kind of RFID architecture where some of the logic is distributed lower in the hierarchy. Filtering and collection is at this stage, where data from several readers is filtered and forwarded to upper level applications according to the needs of each application.

Return channel communication, response information from controlling applications back down to the lower levels of hierarchy, is one of the main questions when implementing networked RFID applications with real-time responses (for example light indicator control at dock door). How far up in the architecture should the control be implemented? For fast responses maybe as close to the actual process and data acquisition as possible, but so far little data or publications exists on details of return channel performance and capabilities in different designs. Figure 39 and Figure 40 from [53] portray well the different phases of operation that we have to look at in detail in order to understand what kind of timing is possible in various RFID systems:

- Operations, meaning air interface delays in reading tags.
- Data acquisition, delays caused by data processing and communication.
- Decision making, time required from application logic to be able to respond (database query etc)
- Actuator action, time delay from logic decision to actual action.

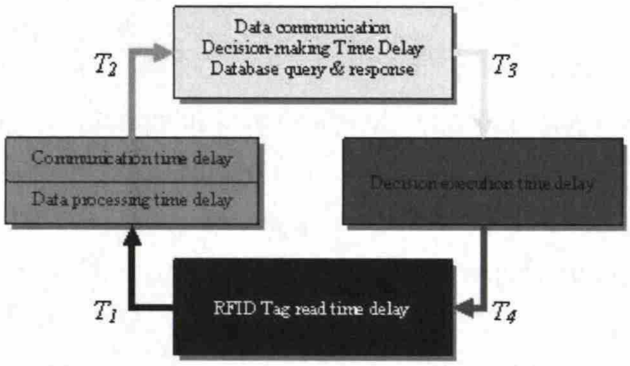


Figure 39 Processes causing delays in RFID systems with respect to real-time response [53]

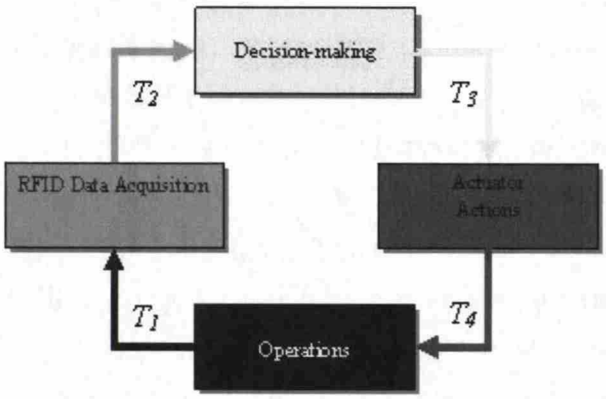


Figure 40 Process steps [53]

This thesis aims to clarifying key issues in systems design, when there are certain real time requirements. An important part of the research is also to produce actual data and measurements about the real time performance of different products on the market, and from real life application deployed in case-study sections.

4.2 Hard real time applications

Hard real-time applications require strict deadlines and extremely reliable operation; all hard deadlines must be always met. Failure to achieve a deadline in a hard real-time application may result in critical failure of the complete system by definition. Critical failure is meaning in this case for example a fatal accident. For example: An aircraft control system is a hard real-time system, as a single flight error might be fatal. Hard real time systems are also sometimes refereed to as safety-critical systems [54].

Could Gen2 technology be used in hard real-time systems? Let's try to think of an example: A train is tagged with a Gen2 tag and there is an automatic system on the side of the track that must guide the train to correct rail depending on the identification. What kind of problems could we face? This kind of system would need 100% reliable reading, the reading would also be quite fast depending on the speed of the train. There should be no possibility for security threats (introduced in section 3.8), such as someone jamming the air interface with a rogue reader. Tags should be durable and there should be no possibility to break one, by accident or by an attacker.

The EPC Gen 2 standard does not contain any specifications concerning minimum time requirements for operations. For example, the time required to execute inventory rounds or other operations in Gen2 depends on many variables, including parameters such as power output, tag density, the surrounding RF environment, air interface parameters, if there are other readers around, and so on. To achieve strict time deadlines in Gen2 systems, we have to look at the system also from many different viewpoints and optimize various parameters in addition to air interface, such as software, hardware, system architecture, messaging protocols, the whole reading process. Currently there are no publications available about Gen2 RFID used in any hard real-time systems and even though Gen2 systems can be optimized for many applications, but still there are still some questions and problems that could prevent using Gen2 in safety critical systems, such as:

- Security issues (See section 3.8)
- Gen2 is a non deterministic protocol – how to guarantee strict deadlines from reading process? (See section 3.3.2)
- 100% reliability nearly impossible to achieve in practice, read rates in practice around 98-99% (tag quality, reader collisions, tag collisions) (See section "*Measurements*")
- Critical performance parameters are not specified by Gen 2 standard and are not evaluated in certification testing

Considering some of the basic characteristics of Gen2 systems we come to the clear conclusion that: *Gen2 systems are not suitable for hard real-time applications.*

After this conclusion we are going to concentrate more on the soft real-time applications. We are going to find out how can we achieve as reliable and accurate Gen2 systems as possible that can be applied in cases where we have real-time requirements, but only so called “soft” real-time requirements. Also in many applications strict deadlines are not present, but timely and fast operation is a requirement.

4.3 Soft real time applications

By definition a soft real-time system is not safety critical, and if a deadline is missed no catastrophe can result [54]. In soft real-time applications the average response time performance is important. Failure to meet operational deadlines occasionally can be tolerated, but may be highly unwanted for economic reasons for example. Because design and implementation of and hard real-time system is often also very costly, as they need special hardware, special software (e.g. RT databases), autonomous capabilities for error detection and recovery etc, it is often reasonable to design a system with soft deadlines even if occasional failures cause some economic loss. [54]

Gen2 systems seem to be suitable for many soft real-time applications. The main constraints seem to be the amount of time allowed for response and the level of reliability needed. The average time and pace of operations must be within the limits of Gen2 and the whole system architecture if responses are coming from upper level applications. Reliability is often measured in Gen2 systems with read rates (how many percent of tags were read successfully) and many times applications or business reasons set a requirement for achieving certain read rate level.

Examples of soft real-time Gen2 applications:

- Manufacturing operations controlled for an item on conveyor belt according to data on tag (Error in reading can cause false operation or even stop in production line)
- Industrial robot moves items into different piles according to tag (Throughput depends on reading speed)
- Software loaded to electronics device according to serial number on tag (Error in reading prevents operation)
- Product specific data written to tag on manufacturing line (Manufacturing capacity depends on writing time, optimal writing time increases throughput)

- Traffic light control according to pallet tag on a warehouse dock door (Long response time causes unnecessary waiting in loading)
- Roll cages leaving warehouse identified at dock door (High read rate required, missed roll cages may be lost)

The following sections describe common Gen2 optimization problems and solutions.

4.4 Protocol standard and air interface limitations

Air interface is the first step that needs to be optimized in order to achieve fast response times and reliability in Gen2 systems. It is limited by the basic properties of technology and i system design we have to take into account the limitations of air interface. Optimizing the air interface is the basis for successful deployment of any Gen2 application. Problems caused by poor air interface settings cannot be fixed in higher level components.

Unfortunately Ge2 standard is not versatile enough in practice that it could perform well with one set of settings in all application areas. In some applications Gen2 tags are needed to be identified at fast speeds, in some the readers may be operating in noisy environments or in some cases the amount of tags present may be varying.

There are several factors that affect Gen air interface performance, and when implementing a new application we should always evaluate the variables affecting reading in each situation.

- How many readers are operating in same area; are we going to have reader collision problems?
- How fast reading must be?
- How many tags are present in antenna field?
- What is the reading distance?
- Is RF environment noisy or not?

Air Interface / Real time capabilities	1SO8000-6
Type	**Passive (Gen2)**
Wake Up length	**500ms**
Anti collision slot	**2-3ms**
Time to detect 1000 tags (32 bytes data)	**3-5s (aprox.))**
Av Tag read time (UID + 32 data bytes)	**<500ms**
Max. Passing speed	**~50km/h**
Time to detect 100 tags with minimum 99.9%	**<10s**

Table 14. Comparison of real time capabilities of ISO18000-6 / Gen2 standard [32]

Common air interface related reading problems in real-time applications are:

- Fast moving objects. Tags missed when tagged object move fast across antenna field.
- Noisy RF environment limits reading and causes random tags to be missed.
- Large batch of tags in front of antenna only partially inventoried. E.g. only 50/100 tags inventoried.
- Unnecessary duplicate reads
- Handheld reader disturbs fixed reader operation randomly

[58]

4.4.1 Reading speeds

In Gen2 systems, the reading speed of tags is limited by the hardware and tag performances as well as the RF environment and the protocol parameters used.

According to the Gen 2 technical specs readers should perform more than 1,500 tag readings per minute in North America and 600 reads per minute in Europe (more restrictions). According to [37] Gen 2 speeds support the ability to identify objects on conveyor belts moving 200 meters per minute, and at reader portals identifying object moving 12 km/h , write rate being about 10 tags per second [26].

Reading speed can also be understood in also different ways: Either simple how many different tags can be read in minute (for example), when a large batch of tags is in front of antenna or as a how quickly a fast moving tag can be inventoried, when the tag is in front of antenna only for a short amount of time? In some cases the reading speed could also mean how many times the same tags can be read in a minute for example. These situations are in Gen2 terms very different indeed. For example, the first case could be characterized with the measurement such as 1500 tag reads per minute as is usually done in case of reader datasheets and in the latter with the maximum amount of time required for tag to stay in the antenna field of view in order to be inventoried each time (50ms for example), this is not a very common case though.

Reading of multiple tags as fast as possible would in optimal case require a long read cycles where each tags would respond at their own slot, minimizing tag to tag collisions and maximizing the amount of inventoried tags per cycle. This kind of setup for Gen2 parameters would have a relatively high Q-value, so that the maximum amount of tags could respond within one cycle. Also a session value with longer quiet time will help if not all tags can be inventoried in one cycle. However, in the case of multiple tags it will always take a relatively long time to do the inventorying.

When as fast as possible identification of single tag is required, the parameters can be tweaked so that individual read cycles are short (low Q-value) and responses quick.

Fastest communication rates between reader and tags can be achieved by optimizing the modulation (FM0 fastest), shortest Tari value possible and fastest BLF value. Using the theoretically fastest values does not necessarily mean fastest operation, because interference can cause fastest methods to fail in communication. Finding the correct values can be estimated according to the RF environment or by testing with a reader that allows parameter changes.

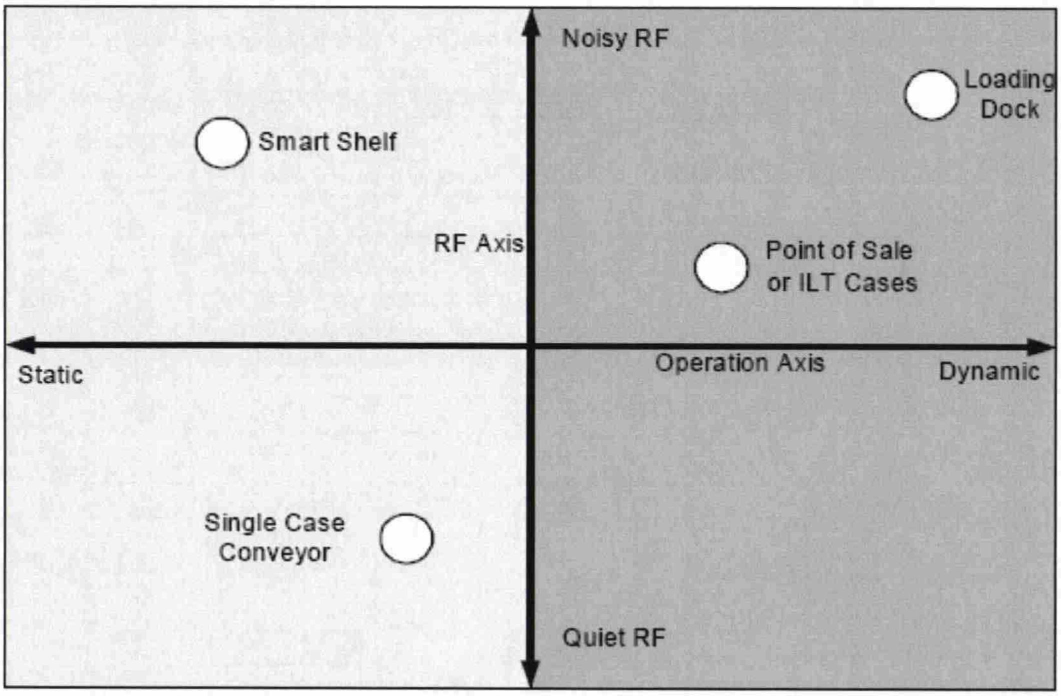


Figure 41 Application Scenarios [59]

Theoretically the communication time needed for tag inventory can be calculated from the protocol standard specifications. If we calculate the theoretical time for identifying one tag in an inventory cycle we can compare that also later on in the measurements to actual values measured.

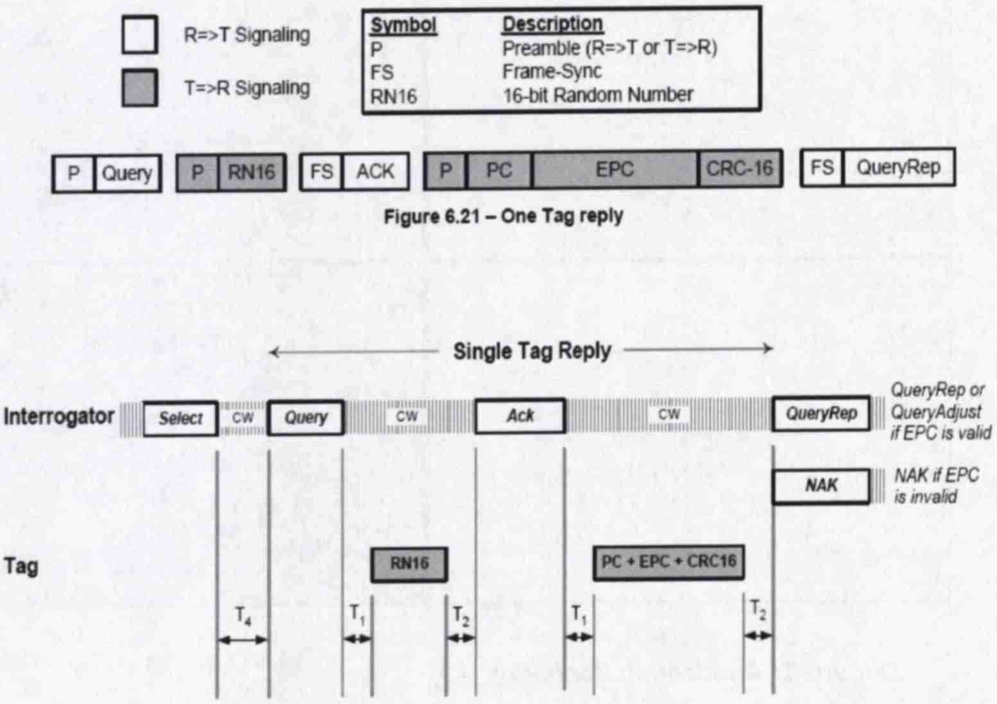


Figure 42. Protocol commands for single tag reply [9]

Here are the calculations for two scenarios: fastest and slowest data rate, all other cases should be in between and this should give us an idea what we can expect.

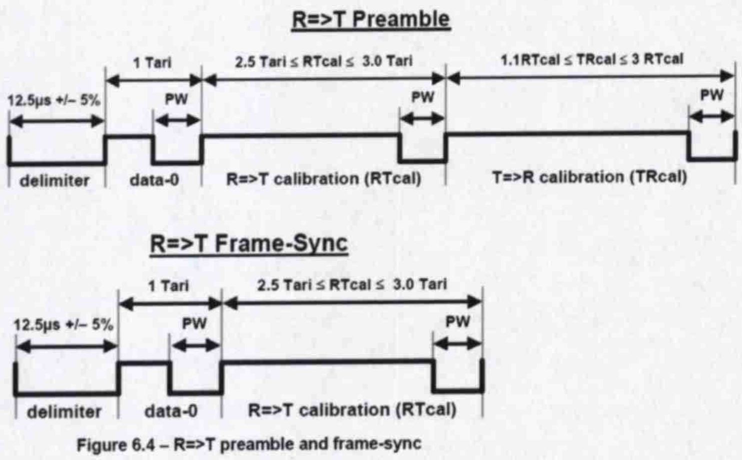


Figure 43. Protocol preamble and frame sync lengths [9]

Parameters	**Time (us) / slow**	**Time (us) / fastest**
Data rate (kb/s)	40	640,00
Tari (Tpri)	25	6,25
Rtcal (2.5-3xTpri)	75	15,625
Trcal (1.1-3xRTcal)	225	17,1875
T1 (MAX(Rtcal, 10xTpri)x(1-/+FT)-/+2us	252	62,50
T2 (min 3xTpri, max 20xTpri)	500	18,75
T3 (0xTpri)	0	0,00
T4 (2xRTcal)	150	31,25
Tag to Rdr data-1	25	6,25
Rdr to Tag data-1	37,5	9,375
Modulation	FM0	FM0
Action	**Time (us) / slow**	**Time (us) / fast**
Tag power-up timing	1500	1500
Preamble	337,5	51,5625
Query-command (22bits)	825	206,25
T1	252	62,50
FM0-preambe (TRex=1)	450	112,50
Query response (16bits)	400	100
T2	500	18,75
FrameSync	112,5	34,375
ACK-command (18bits)	675	112,5
T1	252	62,5
FM0-preambe (TRex=1)	450	112,5
ACK-response (PC+EPC+CRC16 = 128bits)	3200	800,0
Total:	***8954***	***3173,44***
FrameSync	112,5	34,375
Select command (45+bitmask bits)	3525	281,25
Select bitmask length (worst case 96)	96	0
T4	150	31,25
Total:	***12837,5***	***3520,31***

We can see from the calculations that the theoretical minimum time for inventorying a single tag is at fastest data rates about 3.5ms. According to Gen2 specifications it does not seem possible to be able to reach faster inventory times. It is likely that the fastest rates are difficult to achieve in practice, but the second calculations for slower data rates show numbers that we can assume to be achievable in real applications, also including select-function with a full bitmask.

Identification of fast moving objects was one of the main problems introduced in the beginning of the thesis. From these calculations we can estimate some maximum speeds for identifying fast moving tagged items: For example identifying a car moving though and antenna field of 1m. This would give us the maximum speed of:

$$\frac{1m}{0{,}0035s} \approx 285m/s\,.$$

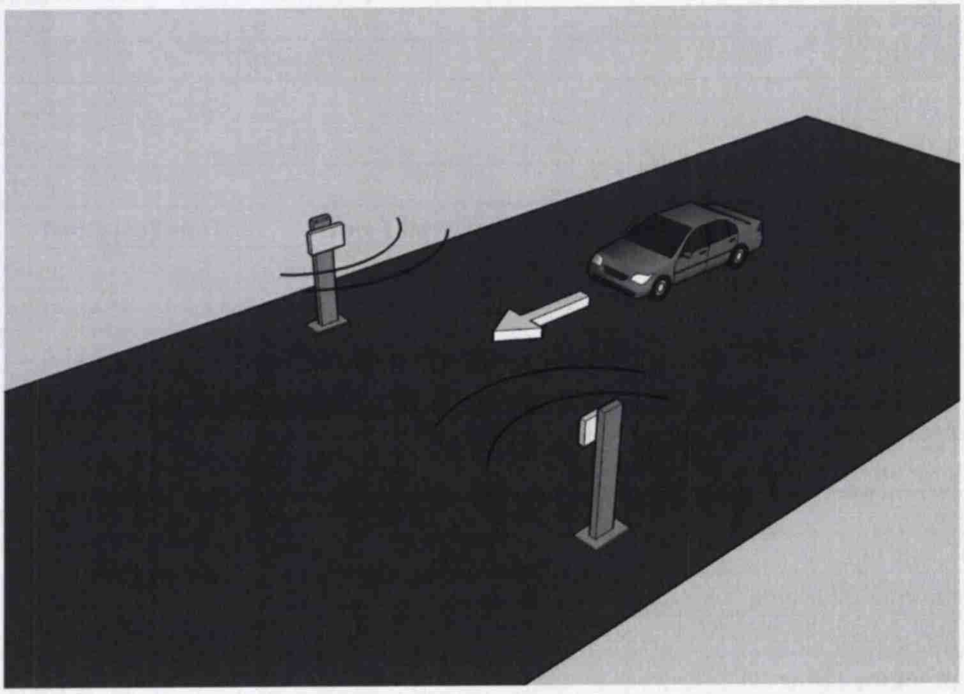


Figure 44, Maximum speed for identifying a moving vehicle would be theoretically 130km/h if we estimate the antenna covers area of 1m with strong RF field

Taking into account conditions outside laboratory with RF noise on affecting data rates, longer of communication sequence with select command and also the fact that a tag may enter the field at any moment (also just after one round has started, not hearing the initial query command) we should expect results such as:

$$\frac{1m}{2\times 0{,}013s} \approx 38m/s \approx 130km/h$$

According to the calculations the time required for identifying a tag is between 3.5 and 13ms. Results for single tag response time in measurements later on should be between these limits. The real question is then: How close can we get to the minimum?

4.4.2 Tag to tag interference

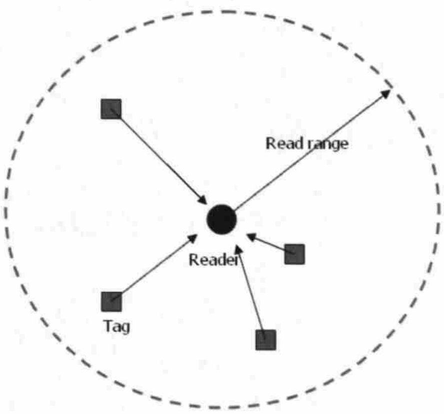


Figure 45. Tag to tag interference; multiple tags in field of view

Tags to tag collisions in a multi-tag environment in Gen2 are managed by optimizing the Q-value, sessions and also by using the group select function. Common problems with Q-value related problems:

- Q-value not optimized at all – reading seems to work (tags seen), but read rates low and inventory times vary a lot.
- More tags in reader field than expected (more collisions) – performance lower than expected or tested
- Session 0 used when more than 50 tags present: Reader missing random tags on every read cycle
- Group select not used: Reader inventories unnecessary tags.

Sessions have a special property that makes tags quiet for various time windows after singulation. This can be used in two ways: If we need to have several tag reads from the same tag (direction sensing applications for example need that), we can use S0 to make sure all tags always respond. In a situation where we have multiple tags present and we only need one read for each of them, we can use S1/S2 or even S3 that have longer quiet times between inventory rounds. Using S1,S2 or S3 keeps tags quiet maybe even for several seconds (limits specified by Gen2, but is tag specific) and that helps when only a part of the tags respond to an inventory round, however for the first query they always responds which makes sure none of the tags are missed because of long quiet time.

Group select can be used to determine which tags should be taking part in inventory and that can be used to leave out unnecessary tags and thus shorten inventory times and help avoid missing tags because of collisions.

4.4.3 Reader to reader collisions and LBT problems

There are basically two types of reader collision problems: Reader-tag collisions and reader-reader collisions.

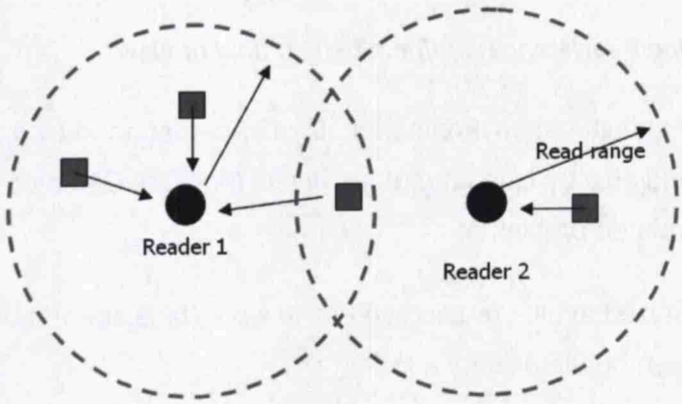


Figure 46 Reader to tag collision

A reader to tag collision occurs when a tag hears multiple readers at the same time. In this situation, the tag might be unable to respond to any reader at all. Gen2 session parameters (3.3.2) can be used to separate readers in different sessions, which enables up to four different readers to inventory same tags simultaneously. Dense reader mode separates frequency channels for readers and enables tags to separate two readers transmitting at the same time, if the they on different channels.

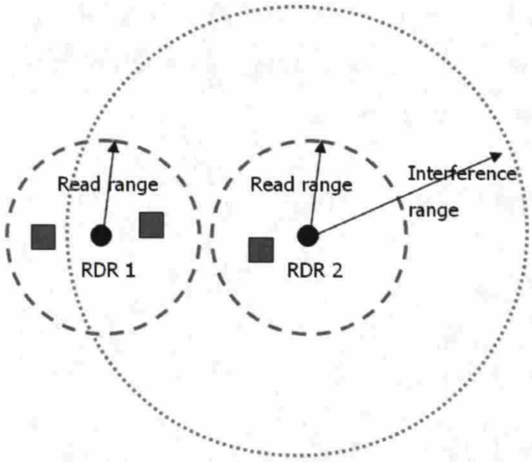


Figure 47. Reader to reader collision

Multi-reader environments may suffer from reader to reader collisions because there may not be enough channels to separate readers. In this case we have to do frequency planning, which means planning what frequency channels are used for each reader so that interfering readers are placed as far as possible from each other.

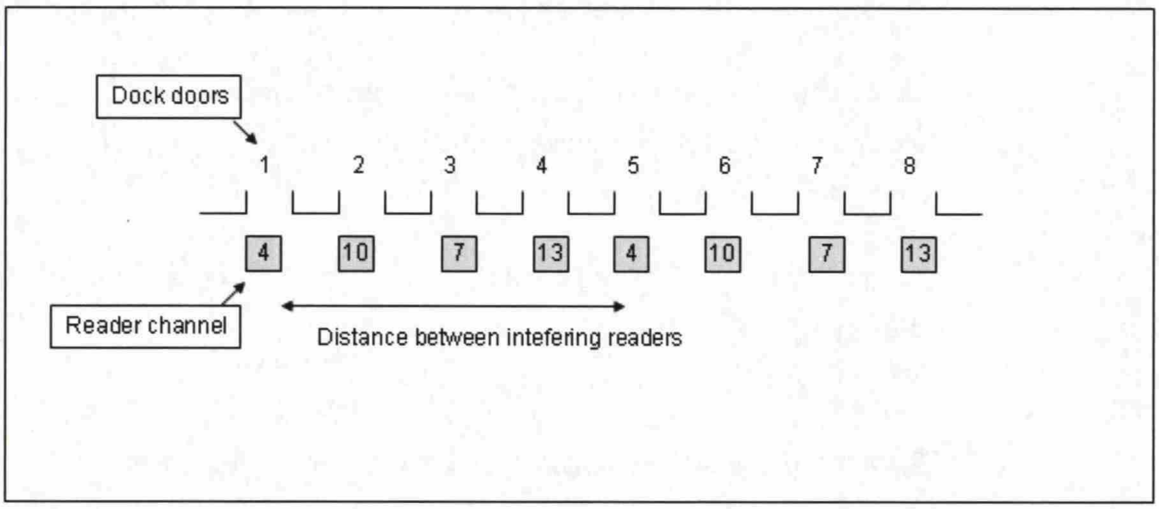


Figure 48 Frequency planning in a dock door installation

In North America there are 50 channels allocated from the UHF RFID band, in EU 15 channels and in Japan 9 channels. Applying DRM to these channel restrictions we notice, that it is easier to implement multi-reader installations in the FCC region than in Europe. In logistics application, many cross-docking warehouses, for example, may require operation of more than 20~30 interrogator at the same time [*38*].

Radio frequency regulations (ETSI in Europe, FCC in North America) also try to limits this issue with synchronization techniques for readers operating in the same channel. LBT and FHSS were applied for this purpose.

- FHSS (Frequency hopping, Spread Spectrum) [FCC]
  - reader must jump every 0.4s to different channel
- LBT (Listen-Before-Talk) [ETSI EN 302 208]
  - If rdr wants to transmit: listen first (5 ms)
  - If background level < -90 dBm -> ok to transmit
  - else wait for random time and try again

LBT especially can cause problems in multi-reader environments, which result in a behavior such as:

- Reader is constantly trying to find a free channel, but is prohibited from transmitting when some other source bocks all channels. No tag reads at all.
- Some of the tags are missed randomly, when reader has to spend time looking for an empty channel. All readers in area seem to miss tags randomly.
- All applications in ETSI region must tolerate 5ms latency in reading in any phase.

4.5 Protocol parameter optimization

The EPC Gen2 protocol allows some protocol parameters to be changed and configured in order to cope with different applications and environments.

. The Gen 2 standard allows the user to include in an inventory round only tags that meet certain selection criteria. This is intended to simplify the job of filtering a tag population to find just tags of interest.[42]

4.5.1 Q-value

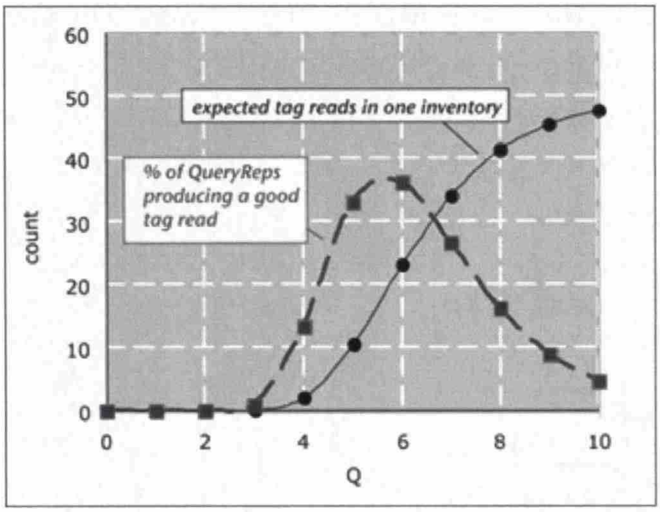


Figure 49 Optimal q-value range []

Q-value corresponds to the number of slots in the communication sequence when inventorying tags. Setting a correct value is basically balancing between minimizing the amount of empty slots (as low value as possible) and keeping the value high enough to avoid collisions (as high as necessary). Due to the fact that tags select slot counter values randomly, there may always be a collision – even if the Q-value is relative high compared to the amount of tags though. It is a probability function, and optimal value can be estimated to be 2^{Q}-1 equaling the number of tags.

Tag population	Optimal Q-value
1	1
63	6
255	8
1023	10
32767	15

Many of the readers on the market also use automatic algorithms for adjusting the Q-value on the fly, such as illustrated in Figure 50. Automatic Q-value adjusting algorithm [9]. The values used in dynamic Q-value adjusting can sometimes be specified, such as the starting q-value, minimum q-value and maximum q-value. These configurations can be used to optimize reading speeds in cases where w can estimate the amount of tags to be within some limits and we cannot wait for the reader algorithm to find correct optimal values by itself.

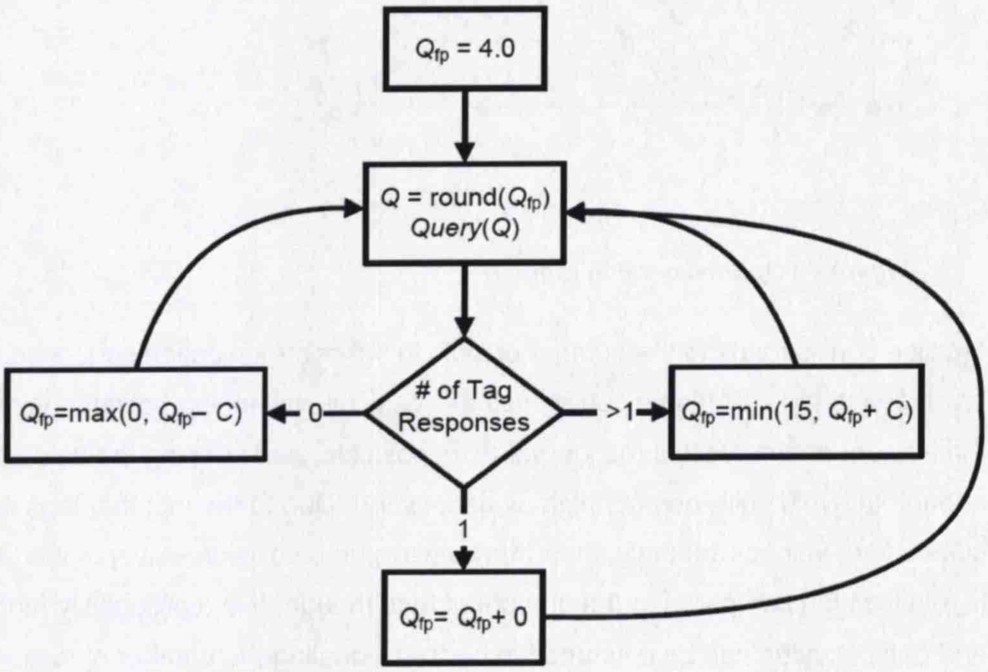


Figure 50. Automatic Q-value adjusting algorithm [9]

4.5.2 Sessions

Session value is optimized according to the time that we need to have the tags quiet between reads. This correlates directly into the number of tags that we need to inventory at the same time. Generalized rules would be:

- Over 50 tags -> S1,S2,S3
- Multiple tags reads needed from same tag -> S0 (S1 possibly)
- Hundreds/thousands of tags -> S2,S3

4.5.3 Inventorying large tag populations with group select function

In environments where we have large tag populations present, but inventorying all of them is not necessary, we can take advantage of Gen2 feature called the "group select". In situations, such as where we have large amount of tagged items on a pallet going through a portal reader, but only pallet label is the one that we need to read, the group select is useful. As long as the tags are encoded with different scheme, "group select" can be used to inventory tags with certain data structure, limiting the inventory responses on the RF level. The important point in this function is that it must be implemented on the RF level in the reader, not only on the software level. The "group select" functionality reduces the amount of time needed for finding certain tags from large populations [26].

An example of "group select" usage would be a pallet, marked with a EPC SSCC code on the pallet label, containing 1500 small boxes, each having an item level EPC SGTIN tag. Inventorying normally over 1500 tags could take up to several seconds, if we expect that read rate is around 250 tags per seconds in optimum case then 1500 tags would require at least 6 seconds. In practice, setting q value high enough might be limited by the reader and even with session values set to 2 or 3 the same tags will also be responding several times on different read cycles, so it wont always be 250 unique tags that respond. However the time for reading on a portal gate is usually limited, as the pallet is moving through antenna field at some speed, slow usually (something close to walking speed). So, in this case normal inventory function at the gate would result in operation where pallet label is sometimes read and sometimes missed at random, depending on how much luck we have with the pallet tag responding in time or not. So, even in a case where the actual movement speed is not very fast, "group select" usage is needed to successfully meet real time requirements [26].

4.5.4 Class 2 tags: TID, Memory reading speeds

Class-2 tags may contain a Tag ID (TID), a hard coded serial number by manufacturer, and user memory for storing data. Accessing TID and user memory require so called access level command to be used for the tag. In order to reach the access level state we have to go through select and inventory process. Basically this means that an inventory round and select command has to be issued before accessing TID or memory – that in turn translates into a longer communication process between reader and tag.

4.6 Data acquisition and reader level problems

Data acquisition from the readers is an important part of designing a real time capable RFID system. Capability of readers to deliver messages in a fast and efficient way is not as obvious as it would seem like. Even if it is possible to optimize the air interface for fast reading of tags, it might be difficult for the reader firmware to deliver messages from tag read to a controlling application in a fast way.

When fast response times are needed, the delays caused by data acquisition may have to be optimized by using low level communication protocols that are able to deliver instantaneous messaging from events. In some applications using low level protocols is however too heavy for networks loads etc (e.g. 100 readers in network connecting to a central server). Large reader networks call for a higher level protocol able to operate more autonomously during network breaks etc.

4.7 Integrating sensors

Implementing triggered reading for a sensor input signal is common in Gen2 systems to avoid collision problems in the air interface. Correct sensor choice and proper usage are important when integrating sensors in RFID systems. Wrong types of sensors or poor configuration of sensors can cause reading problems.

When designing sensors for RFID systems we have to be careful not to cause more problems due to missed triggering in read rates than we want to gain with using sensors after all (avoid air interface problems).

4.7.1 Sensors in conveyor belt applications

Conveyor belt applications require often fast and accurate triggering, but are easy in the sense that the environment is usually well controlled. Light switches (visible light, IR laser) are commonly used in conveyor belt applications because they can be accurately positioned and give fast and reliable response in controlled environments (indoors, objects move in predictable paths, etc). Motion sensors reacting to human movement and surroundings may be a poor choice for conveyor belt applications.

4.7.2 Sensors in dock doors and gates

Dock doors are more difficult to control with sensors than conveyor belts: Identified object are varying (in size, material, shape), there are people moving back and forth through gates, sometimes forklifts. Sometimes loading gates can also be partly outdoors and be affected by rain, snow and temperature changes.

Motion sensors are mainly used for triggering RFID readers in dock door and gate applications. They can be used outdoors and are designed to trigger output signal when a person enters the sensor field of view. Most commonly used basic type is a PIR, Passive Infrared, sensor that looks for body heat – and no energy is emitted from the sensor. They can detect a moving person (heat source) to distance of approximately 10m, at a fairly wide angle. Ultrasonic or microwave sensors may also be used in some cases, they can detect more accurate movement, longer ranges and objects that do not emit heat. A microwave sensor could also be used. It sends out microwave pulses and measures the reflection off a moving object. Motions sensors may have delayed triggering and the conditions for triggering can vary due to different operation when temperature changes for example. Triggering for PIR sensors in winter conditions is also difficult, because snow and ice may cover the sensors.

4.8 System architecture level and decision making logic

A key question in design of an RFID system is: Where to implement decision making? Where in the architecture it needs to be implemented in order to achieve certain level of response?

Generally (according to EPCglobal Network Architecture) it is suggested that decision making logic is placed as high in the architecture as possible. It Is considered as the job of high level components to implement business logic. However, for response times this basically means as slow response as possible, since the input data has to travel all the way through the system to reach decision making logic and then all the way back down to readers (or actuators).

For fast response we may have place so part of the logic lower in the hierarchy, it might actually be nearly anywhere in between. For fastest possible response it is implemented in the reader software itself. Sometimes a good solution is in the data collecting middleware if it is possible implement custom logic on that level.

A common problem for RFID systems is that response times are designed to a small (many times pilot level) system that start growing in number of readers. Response times start getting longer as more readers are added to the system. For a system that waits for response from highest level components such as ERP systems, it might be possible to get acceptable response time for single reader system (or low amount of readers), but if the system grows to include more readers the performance drops.

4.8.1 Return channel

Equally important to the placement of decision making logic is the implementation of return channel communication. Only lately EPCglobal has added return channel operations to the ALE specification for example [5] and previously it was not included in the specification in any way. Return channel implementation are however so varying that it is difficult to set a standard way for implementation. For commanding RFID readers it is easy: Implementation also that aspect of reader protocols (write commands/kill commands/lock commands). In readers level the return channel communication can be implemented as totally separate channel, as in the RP1.1 for example that specifies a so called “command channel” or in some other proprietary ways, such as in Motorola readers in a protocol for both ways communication on byte level. In many cases the endpoint of return channel might not be a RFID reader. It can be some other device such as industrial robot, actuator or IO device. For those cases we may have to develop custom software components that are able handle communication.

5 PERFORMANCE MEASUREMENTS

In order to determine the possibilities of UHF RFID in real time applications I tried to first measure performance in laboratory environment. These measurements are meant to be a reference point for the performance in real life applications. The measurements are also done to find out the performance in optimal case – what is the maximum reading speed, for example, in practice. These measurements should give us limits for what is possible and what is not, what kind of response times we can expect.

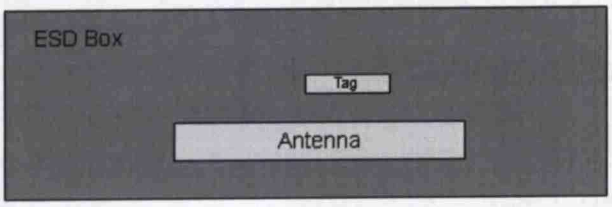
Target of the measurements:

- Find out maximum reading and writing speed, minimum time to identify a tag
- Find out effect of Gen2 parameters
- Find out the response time for full layered system architecture

5.1 Reader measurements

In reader measurements the purpose was to determine the capabilities of current Gen2 RFID readers and tags. The limitations of the Gen2 specification itself were calculated earlier on theoretical level. In this section we can also compare real results to theory. Test cases and test environment were optimized for maximum reading performance as much as possible in normal office environment, so that we could get as close to minimizing other variables as possible.

In measurements for optimal performance (reference), we tried to minimize the effects of RF environment. It was done so that the reader and antenna was placed inside a shielded box and tags close to the antenna in an optimal orientation – eliminating the disturbance caused by environment RF noise and other readers. Eliminating communication collisions from other readers or tags assured that communication of reader and tag could be done with optimal RF parameters. Tag was always in same position and distance. Carrie wave sent by the reader was strong at the position of the tag and sufficient to keep tag powered up constantly. RF environment was verified with spectrum analyzer before and during the test.



Equipment needed for these measurements were: Gen2 RFID readers (e.g. Impinj URP1000 and Motorola XR480), UHF RFID antennas with necessary cables and a spectrum analyzer (up to UHF RFID frequency range, 1GHz) and a laptop/pc for running tests. Special software was developed for the tests to record tag reading timestamps on millisecond accuracy from the software level and from reader level (provided by reader communication interface). Timestamp based measurements were verified by another set of measurements where we measured time externally from start of reading to the identification. Reading was triggered from pc (IO signal into reader's IO port can be used to trigger reading for example) and a timer was set on the software to run until the reader signaled the event of successful tag read (IO output signal or notification message from reader can be used to record this event).

Measurements for determining performance in real world cases and applications have been done in a typical production environment where background noise, other RF devices and also other RFID readers cause disturbances.

5.1.1 Software development work

Software that was developed in order to make these measurements was mainly relying on the timestamp information provided by the reader itself and thus there was no need for accurate timestamp measurements from the software side. Software was implemented using Microsoft .NET 2.0 and Visual Studio. The main components were: reader communication layer (for three different reader interfaces), data collection and storage and user interface. To be able to communicate with readers Mach1 protocol driver (CSL, Elektrobit and Impinj devices) and a ByteStream Protocol (Motorola device protocol) driver was used. Also an LLRP driver was tested with Impinj reader. Driver classes implement the commands that are necessary for reader communication. Basically the reader drivers implemented basic "start reading" and "stop reading" type of commands, and also the settings of different parameters. As an output the drivers they converted tag data from the reader's specific formats into unified type of TagEvent objects and put them into a collection of objects. Software also included visualization of read rate and a read cycle length by graphs that were implemented by using free C# library from ZedGraph (http://zedgraph.org/).

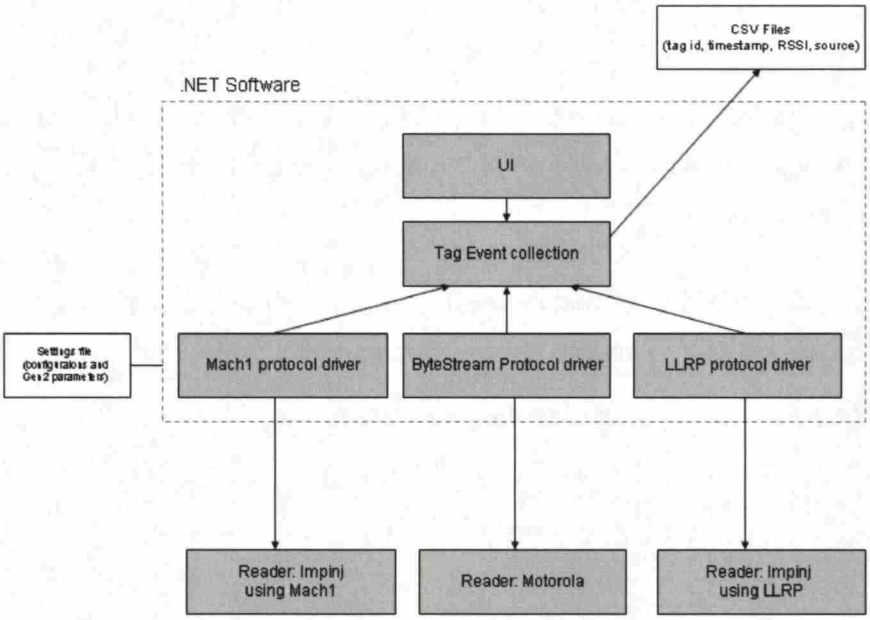


Figure 51 Software components

Analysis of the measurements was done mainly by exporting the data into a csv file and opening that in MS Excel. Graphs and calculations included in this thesis work were done by using Excel.

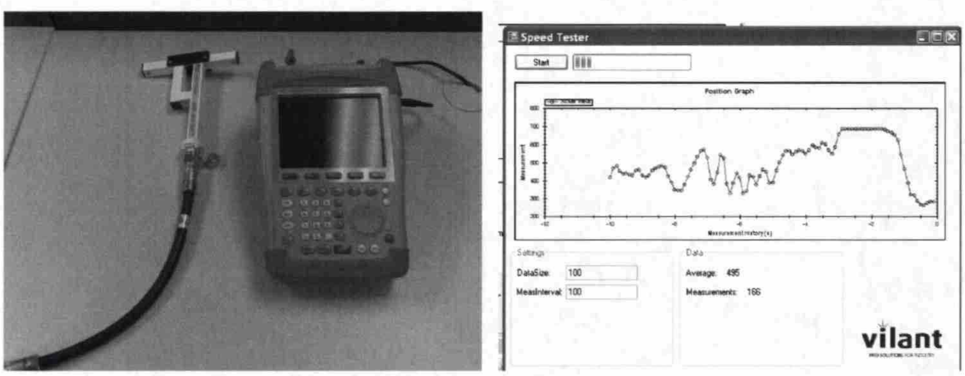


Figure 52. Test setup and a screen capture from test software

5.1.2 Determine minimum inventory cycle lengths

In this first measurement case I tried to achieve as fast of a read response as possible. This measurement was done to find out a reference point for other measurement and also to find out the maximum capability of current readers and tag chips.

This result will also give an answer to the question: How can we identify fast moving tagged items? Application examples could be e.g. identification of cars, trains or other vehicles on the fly.

Measurement was done with fastest possible communications rates (FM0), minimum Q value, only 1 tag and no noise environment.

Table 15. RF parameters used for optimal case testing

Pie	1.5 vs 1
Session	0
Number of antennas	1 (ETSI/UHF)
Region	ETSI-NO LBT
PW	0,33 (short)
Number of tags	1
Tari	6.25 μs
Modulation	PR_ASK
Tag to reader link freq	640 kHez
Tag to reader modulation	FM0
Divide ratio	64/3
Q value	1
Session	0
Modulation	FM0
Data rate	640kHz

Table 16. Short distance, shielded environment

Tag chip type	Inventory time (average)	Inventory time (min)	Inventory time (max)
Impinj Monza3	8,0ms	7,3ms	9,1ms
NXP G2XL	8,1ms	7,0ms	9,9ms

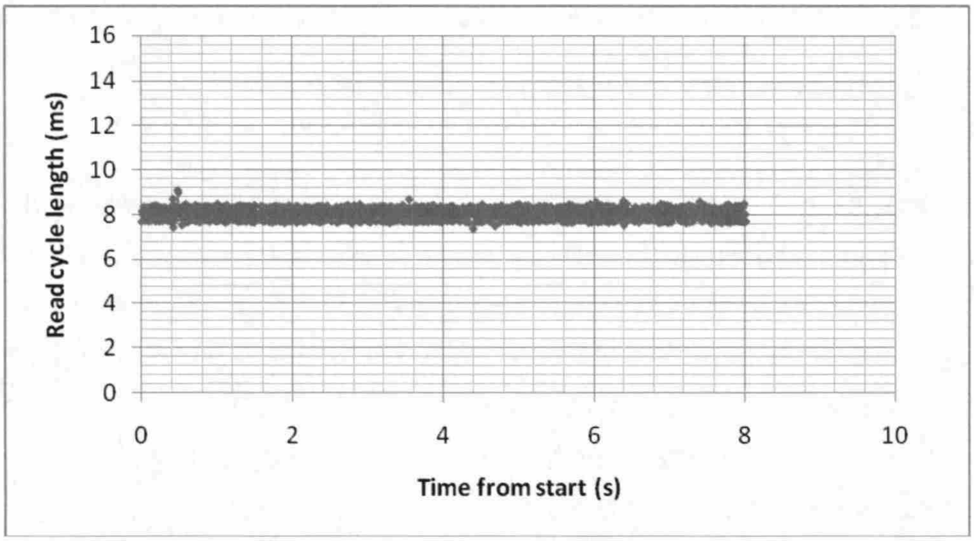


Figure 53.Read cycle length plotted (Monza 3 chip)

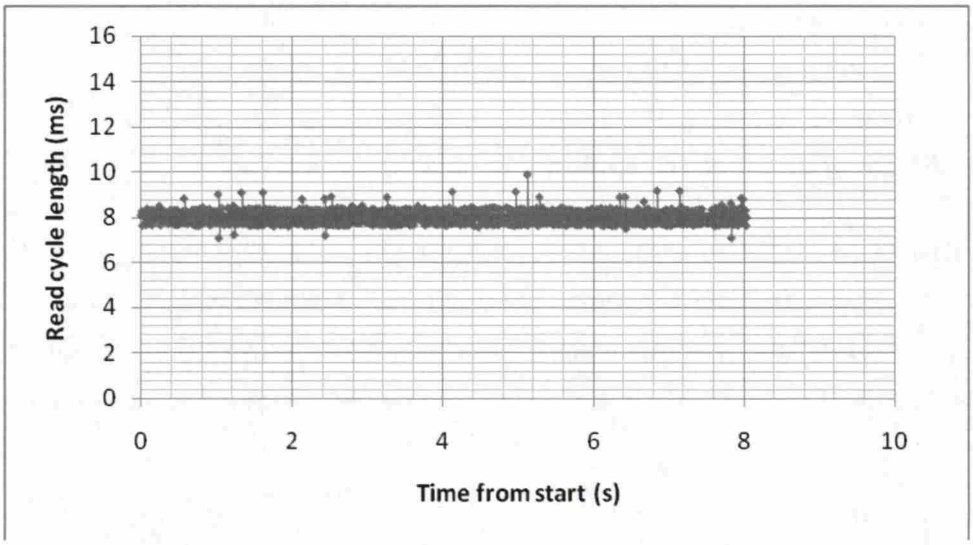


Figure 54. Read cycle length (NXP G2XL chip)

These test results show that in optimal conditions under 10ms response can be achieved for single tag reply. Compared to the theoretical minimum (3,5ms) that we have calculated earlier it seems that there is about 4ms difference. There was no significant difference in comparison of the two most common and recent tag chip types.

5.1.2.1 Identification of fast moving target

According to these numbers identification of fast moving target could be estimated. For example we can estimate that a strong antenna field of 1m could be realistic when a fast moving tagged item, such as a car, is moving through an antenna field.

This would give us the maximum speed of $\frac{1m}{0{,}010s} = 100m/s$.

This number seems to be the absolute maximum speed possible to reach with currently commonly used UHF RFID readers. In reality we have divide this number at least by two to make sure to include the tag into at least one inventory round, because the tag may enter field of view at any given time during inventory. That would give us 50 m/s max speed. However, we can see from the later measurements that the reader cannot do all inventory rounds as fast as this when distance is increased between tag and antenna.

Calculating the maximum speed for average reader speed would be:

$$\frac{1m}{2\times 0{,}010s} = 50m/s$$

5.1.3 Effect of distance to reading speed

The effect of distance has already been studied earlier, for example in [20] K. N. Moncombu Ramakrishnan has measured response rates versus distance and attenuation. The result was that there is no difference as long as the tag remains in a strong RF field and only when tag is in too weak field the response rate will drop.

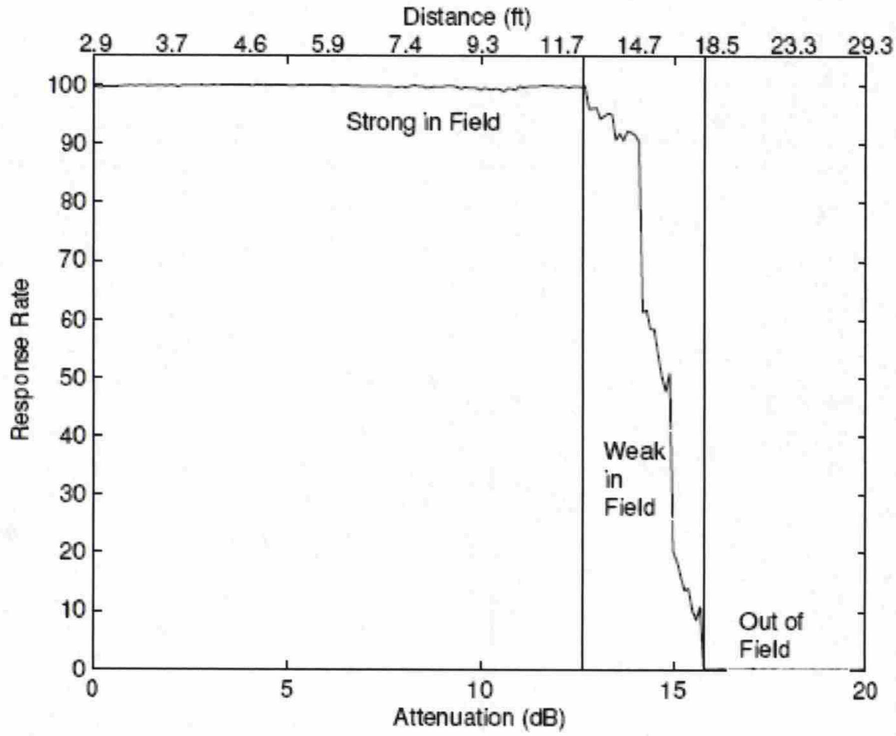


Figure 55. Response rate vs. distance and attenuation from [20]

When reading tags from distance in free air the results show that there is no significant difference in reading speed within strong field, however there were occasional results with lower reading rate compared to the near field reading (optimal case). Mostly the read rate was similar to the optimal case, but some of the reads too from 30 to 40ms longer. Longer reading distance seems to add more variance to response time due to attenuation of the communication signals.

Table 17. Reading from distance, free air

Distance	Inventory time (average)	Inventory time (min)	Inventory time (max)
3m	10,8ms	7,7ms	31,3ms
6m	11,6ms	7,7ms	43,1ms

5.1.4 Identifying a single tag from multi tag environment

Finding a tag from a larger population is expected to take more time, since the inventory round has to listen for responses from all tags. Multiple tags may also cause collisions in the read cycle – extending the read time more.

Table 18. 3m distance, 130 other tags in field, time needed to find a specific tag with complete inventory

Tag chip type	Inventory time (mean)	Inventory time (min)	Inventory time (max)
NXP G2XL	195ms	111ms	226ms

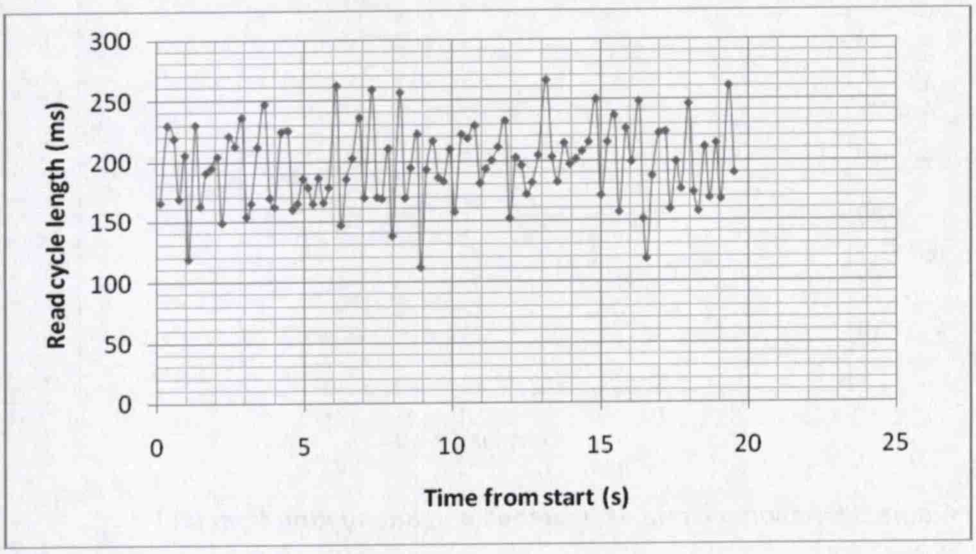


Figure 56. Multi tag reading

Reading multiple tags (130 pcs in field of antenna) and finding a specific tag from the population took from 111ms to 226ms at maximum, average time remained in 195ms. Executing multiple repeats in this test was important, because the tag response is based on random Q-algorithm slots. This means that the time needed for finding a single tag from a population is depending on which random slot the tag chooses and if it happens to collide with some other tag. Longer peaks in the data can be explained by collisions in the inventory. Collision causes a missed inventory round, and should result in about double inventory time compared to average. Potentially the time for finding the correct tag from a large population can take even more time.

One trick that we can use to limit the amount of time needed for identifying tags from a large population is to use a so-called "group select" function. This function basically defines a bit mask for tag epc codes that we can apply for a read cycle limiting the responses only to certain group of tags. For example, in a dock door situation we might have item level tagged pallets moving fast through an RFID gate and there is a difficulty in reading the pallet tag reliably, because a large number of tags on the pallet are also participating in the inventory round. In some cases there might be even thousands of item level tags on a pallet. EPC Gen2 provides this functionality, and it is useful in these kind of situations: inventory on the dock door reader can be limited this way to only allow pallet tags to respond, and item level tags will remain silent. Inventory time to find a tag with this function is expected to be much lower. Function requires that coding of the tags allows differentiation of item and pallet tags for example by a bit mask.

Table 19. 3m distance, 130 other tags in field, time needed to find a tag using group select function

Tag chip type	Inventory time (mean)	Inventory time (min)	Inventory time (max)
NXP G2XL	8,1ms	7,7ms	10ms

As expected, the inventory time in this case was similar to the case where we had only one tag in the field of view. *Group select function can be highly recommended according to this measurement.*

5.1.5 LBT effect

Previous measurements were done with LBT turned off, in order to minimize the time needed. However, the current ETSI regulations still require (6.11.2008, in versions lower than 1.2.1) that LBT technique is used. LBT requires the readers to listen for a short time for other transmissions on a channel – this basically insists that we have to take into account possibility of LBT turning on at any moment.

Table 20. Reading time compared in case LBT mode.

Anti-collision technique	Inventory time (average)	Inventory time (min)	Inventory time (max)
LBT ON	8ms	7ms	55ms
LBT OFF – four channel plan	8ms	7ms	10ms

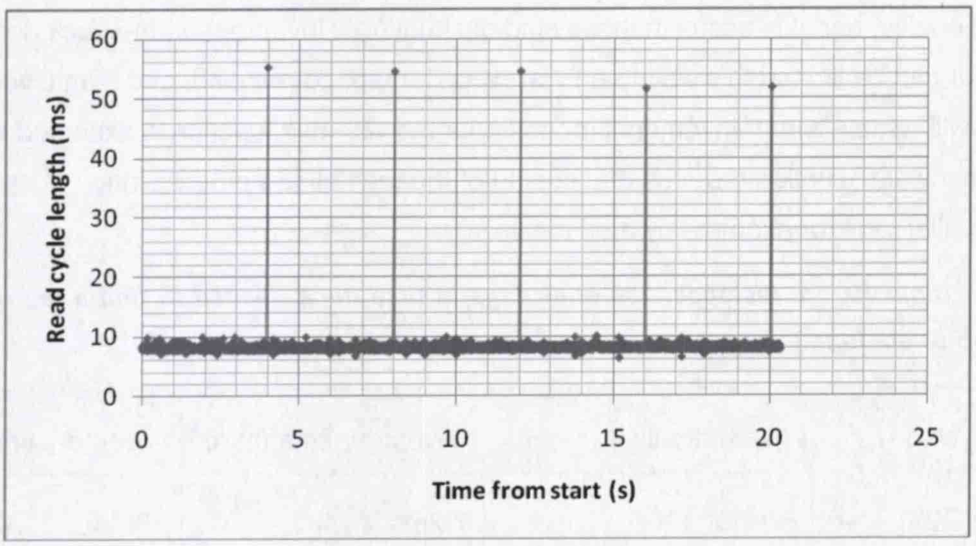


Figure 57. LBT Effect chart

The results show how LBT is causing about 50 to 55ms delays in intervals of 4 seconds. This delay may be much higher if the channel is occupied and the reader has to find another free channel – here there were no other readers. These 4 second intervals corresponds exactly to the ETSI regulations as expected, and has to be taken into account when designing an application requiring high speed reading. The conclusion from this test is that we have to take into account this delay, even though it is apparent only once per every 4 second interval, because it is very difficult to see this during testing (multiple repetitions needed) and is also one reason that may cause "unexplained" missed reads if not taken into account.

LBT effect can be removed by using sensor or other trigger to start reading early and limit reading time, so that it will not need to do another LBT. One other possibility is to use the new ETSI standard (1.2.1) regulations' 4-channel-plan without LBT when it is ratified for use. One possibility is also to use dense reader mode where readers stay on same channel.

5.1.6 Determine minimum writing time

Reading actions in Gen2 can be fast, but writing actions take more time. Writing requires a tag to be identified first from a population and then accessing it with an access command. Only after that new data can be sent with a write command.

Table 21. Writing time, 10cm distance, shielded environment

Tag chip type	Write time (average)	Write time (min)	Write time (max)
NXP G2XL	60ms	46ms	94ms

Writing tag EPC code seems to take about 45-95ms according to the measurement. If an application must include writing to the tag, we have to take into account need for writing time of approximately 100ms in minimum.

5.1.7 Tag population size vs. inventory length

Population size naturally effects the length of the inventory, the purpose of this test is to find out the numbers – what is the effect really going to be?

Table 22. Reading times compared to tag population size

Population	Inventory time (min)	Inventory time (max)	Inventory time (average)
1	7ms	10ms	8ms
10	24ms	71ms	59ms
100	136ms	206ms	157ms

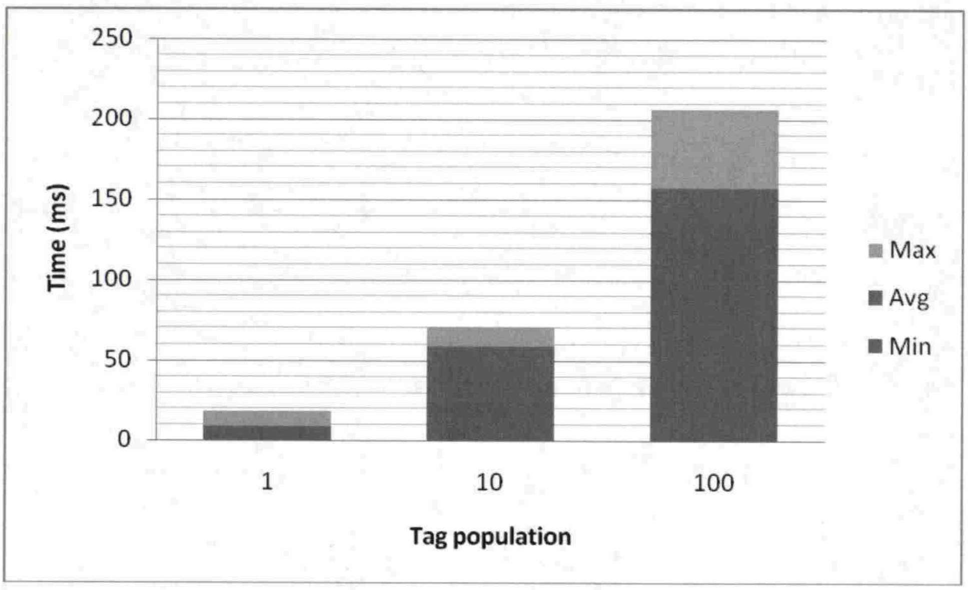


Figure 58. Tag population effect on read time

Increasing the population affects significantly the time needed. In real time applications the number of tags is a crucial factor, fast responses are not possible for large very populations (thousands), most real time applications are however cases where only one or s small number of tags is simultaneously in the field. Expect inventory times to grow up proportionally to the population.

5.1.8 Q-value vs. inventory length

Similar effect of longer inventory time is seen when the Q-value is increased, event though the amount of tags does not change. Inventory cycle is extended because the reader is allocating more timeslots for tag replies. Here the test was conducted with a Motorola XR480 reader. The real effect of Q-value effect is better seen in the results of Motorola reader than for example with Impinj reader, because it allows static setting of Q-value (also allows dynamic setting). Impinj has a built-in algorithm that optimizes Q-value automatically and cuts off read cycles and it cannot be set to a static value. User can only set a starting value for the algorithm for Impinj. Q-value sets the amount of timeslots in the power of 2 and that explains why a much longer time needed for greater values (i.e. amount of tags).

Q	Inventory length measured (ms)	Timeslots	Time per slot calculated from total time	Communication preamble calculated from total time
1	22	1	~0,7ms	~21,3ms
4	33	15	~0,7ms	~21,3ms
6	67	63	~0,7ms	~21,3ms
8	200	255	~0,7ms	~21,3ms

Table 23. Estimates of single timeslot length for Motorola XR480 reader

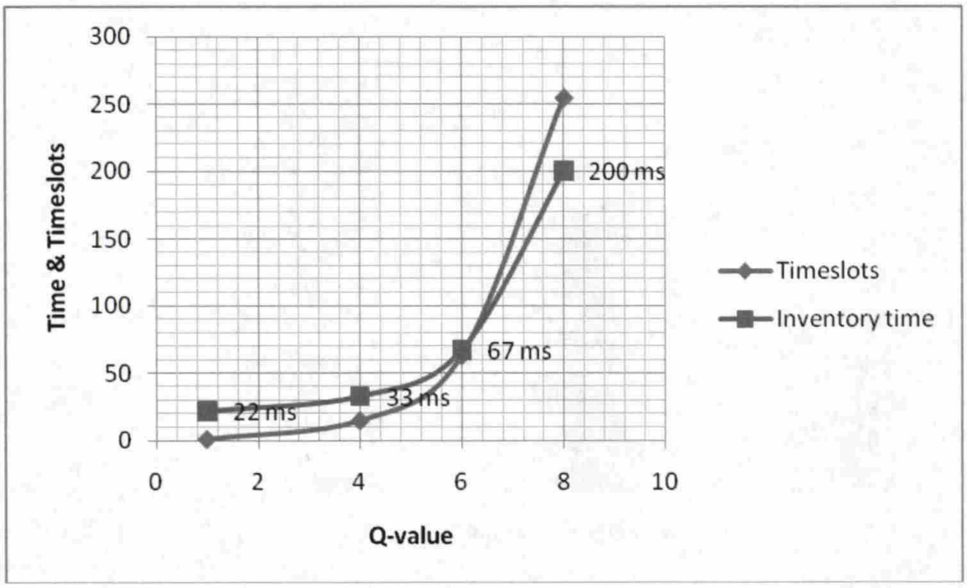


Figure 59. Inventory time relates to Q-value clearly in measurements

5.1.9 Dense reader mode effect

In real world applications we often have to cope with interference caused by other readers in vicinity – not always is it possible to have an optimal environment. Dense reader mode is expected to cause longer cycles, M8 even more than M4.

Mode	Inventory time (average)	Inventory time (min)	Inventory time (max)
Max throughput	8ms	7ms	10ms
Dense reader mode M = 4	12ms	10ms	15ms
Dense reader mode M = 8	17ms	15ms	21ms

Figure 60. Dense reader mode effect on reading speed

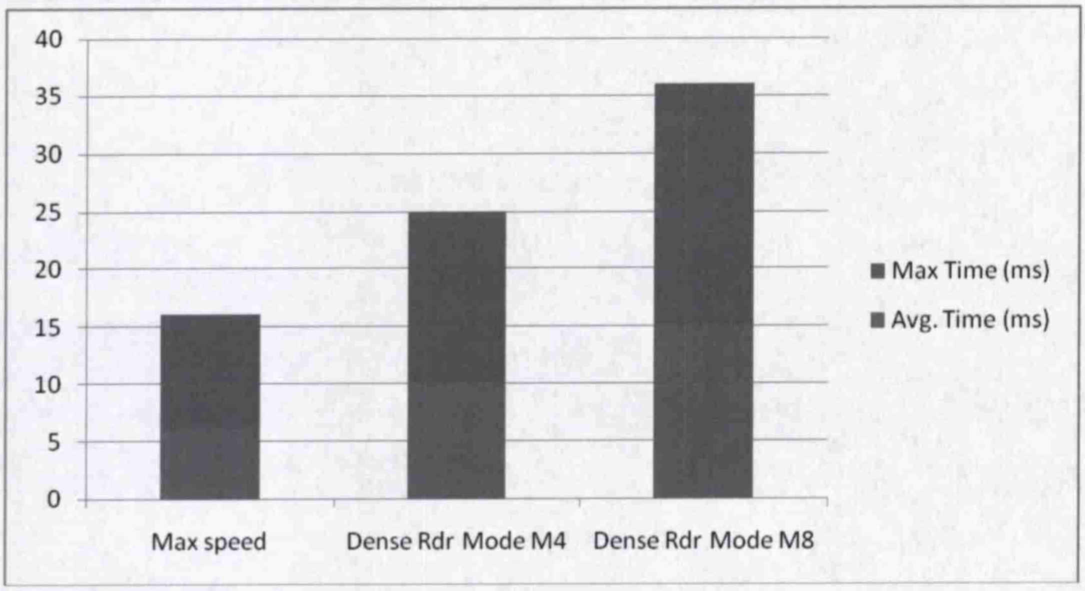


Figure 61. Dense reader mode effect on read cycle

Measurements show exactly the expected result. M8 is the slowest, M4 in the middle. Somewhat surprising is the fact that M8 more than doubled the time needed for reading a tag.

5.1.10 Data rates setting, RF environment noise effect

The last of the measurements was done to check how data rates affect reading time. In this test 100 tags were inventoried in two different settings, fastest and slowest data rates. Readers may provide also data rate settings in between these.

Table 24. Data rates effect on inventory time of 100 tags.

Mode	Inventory time (mean)	Inventory time (min)	Inventory time (max)
Fast data rates, low RF noise	157ms	136ms	206ms
Slow data rates, noisy RF environment	433ms	143ms	786ms

Results show that using faster communication rates can give us better performance (possible to have 2-3x increased speed) with speed, as long as the communication link is not broken.

5.2 System level measurements

Other main parts of delays and response time effects in any RFID application are also the software and communication layers (see Figure 39 in chapter 4.1).

The EPCglobal network architecture for RFID applications is based on multiple software components working in a hierarchical, layered nature. Data from the readers is passed through multiple systems before it arrives to the decision making logic. Each level is also designed to operate based on different abstraction levels: The enterprise application does not know anything about the physical reader (Motorola XR480 at IP address 10.0.1.168) that has generated the actual tag reads – for the business logic events are only coming from "locations" (such as "Factory X, distribution center, dock door 2"). This makes an interesting case for real time application requiring return channel actions towards the readers, as the messages have to pass multiple systems and still be fast enough for response actions.

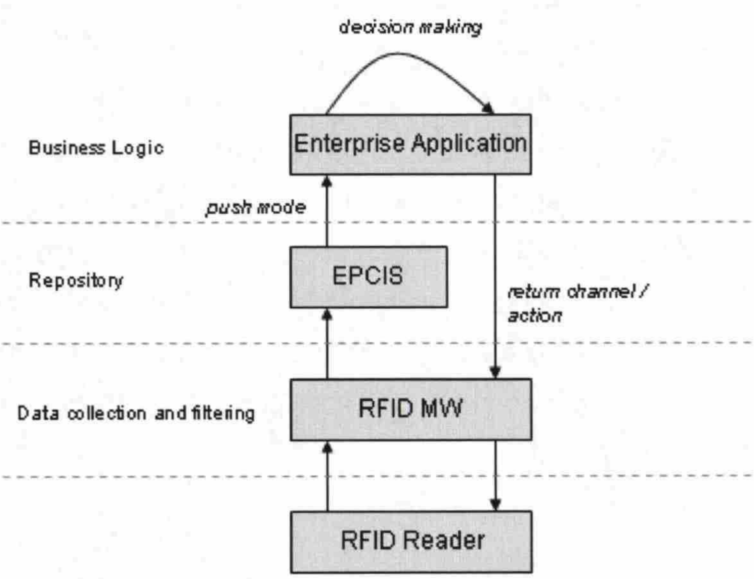


Figure 62. System level measurement case

In this measurement I tried to find out what are the response times and delays caused by different levels in RFID applications. In this case, the return channel actions from the enterprise application have to go through the RFID MW back towards the readers. The repository could be bypassed for return channel actions, but RFID MW is the only component that is able to translate abstract locations and commands into real commands that readers or devices accept (device specific commands). Figure 62. System level measurement case, illustrates the situation. The enterprise application is receiving data from a certain *location* and the command that is sending back to middleware is something like “tag X at *location* Y is OK / NOK”. This message is converted in the RFID MW into a real action such as a message to the reader’s IP address mapped for that *location:* “set GPIO pin 1 high”.

Purpose of this test case is to find out the delays related to event forwarding from one component to another, concentrating on the RFID MW components. A dummy web service call was used to simulate ERP level and the decision making. Web service call returned a response immediately, so this case simulated optimal performance.

Table 25. Results from system level test

	RFID MW to EPCIS (ms)	EPCIS to ERP (ms)	ERP decision making (ms)	ERP to RFID MW (ms)	Total (ms)
AVG delay	***73ms***	***536ms***	**-**	***22ms***	***631ms***
MIN	*47ms*	*673ms*	**-**	*16ms*	***407ms***
MAX	*94ms*	*281ms*	**-**	*32ms*	***736ms***

From the test results we can see that even though there was no delay for the decision making – only RFID part required a round trip time from minimum 407 to max 736ms. The results show that, expecting real time responses below these numbers are unrealistic from the ERP level – with the standard architecture. It seems that the main cause of delay is coming from the EPCIS level, which is the part where large amounts of data is gathered and stored in a database. It may be possible to achieve faster response times by bypassing the slow EPCIS level transactions directly from MW level.

6 CASE STUDIES

6.1 Direction sensing cases

These are cases where direction of movement of tagged objects is identified based on the RFID reads. These applications require a highly optimized setup in order to provide enough information for determine direction.

One of these cases is a typical asset tracking application for UHF RFID where we are doing identification of moving assets at dock door, roll cages in this case, as they move in and out, but with the addition of direction sensing from only RFID based reads at the gate. Previously in similar cases with direction sensing have been implemented with sensors. Also typically in distribution center installations the RFID system does not need to provide direction as there are separate doors for inbound and outbound loading, but in this case there is movement in both directions through the gate.

Direction sensing from RFID reads is a difficult problem, even though the direction solving is typically reduced to A to B or B to A (in/out) type of problem. There are some algorithms developed to estimate the direction from reads, for example from a company called Impinj that offers a direction sensing solution (reader and tag manufacturer). Various RFID software vendors have also developed proprietary algorithms to determine the direction of movement from RFID reads. For example Vilant Systems has developed such a solution for Aker Yards' personnel tracking system [55].

The details of current direction sensing algorithms are not publicly available, but according to Impinj [59] they are based on a special antenna configuration and the algorithms estimates direction and a probability factor from antenna reads. A setup of two or four antennas is needed and the amount of tags in field is limited to 15. Stray tags and stationary tags in field decrease direction sensing performance.

The direction sensing algorithms are basically probability functions and heavily depended on numerous measurements and tag reads from the moving object. With only one measurement from a tag it would be difficult to determine anything, but for example from measurements in Table 26 it would be quite easy to determine direction. We have to remember though that it is always a probability function, but with quite high probability we could say that an item is moving from A to B. To be able to have a high probability, the algorithms need many good reads from tag, even when moving fast. This requires the RF parameters from readers also to be highly optimized. Low Q value, session 0 or at most 1, fast inventory cycles and good signal strength (adjusted to meet RF environment well).

Antenna A	Antenna B
T12:00:00.000; RSSI: 100	
T12:00:00.100; RSSI: 150	
T12:00:00.200; RSSI: 200	
T12:00:00.300; RSSI: 200	T12:00:00.350; RSSI: 100
T12:00:00.400; RSSI: 100	T12:00:00.450; RSSI: 200
	T12:00:00.550; RSSI: 200
	T12:00:00.650; RSSI: 100

Table 26. Example of direction sensing data

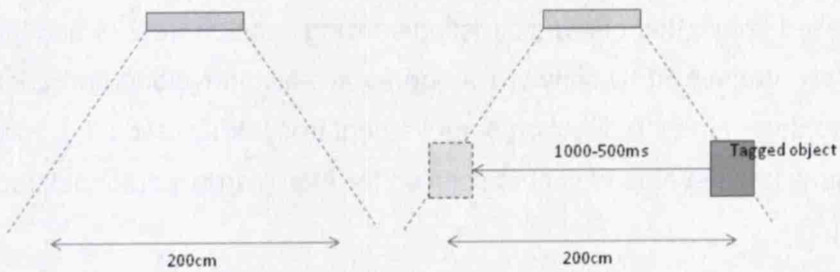


Figure 63. Dual antenna setup for direction sensing in the simplest case

In both cases, the movement speed of tag through the antenna field was generally normal walking speed (1-2 m/s). The antenna's reading field in both cases covered about 2m distance at maximum. For a minimum of one read per antenna, this meant that reading had to be done within 500ms. In the dock door case 4 antennas were needed to cover the dock doors fully, 2 on each side. Multiplexing 4 antennas had to be included in this 500ms time window. In the other case 2 antennas were needed. Also, because the application had to take into account the worst case scenario: A tag enters the field of view of one antenna just as the cycle has already started, it will have to wait for the next inventory round to be included – meaning at least two rounds per each antenna have to fit into the 500ms time window. Dividing this 500ms with 4 antennas and 2 cycles per antenna gave us requirement of 62,5ms read cycle.

Reader	*Successful direction sensing rate / Walking speed*	*Successful direction sensing rate / Running speed*	*Successful direction sensing rate / Forklift*
Motorola XR480	*100% (126/126)*	*100% (100/100)*	*100% (368/368)*
Impinj	*100% (144/144)*	*100% (52/52)*	*100% (300/300)*

Table 27. Direction sensing test results from distribution center dock door case

The dock door solution was tested thoroughly and it was concluded from the results that direction sensing was working on a good level. Amount of repetitions was high enough to prove at least 99% successful direction sensing rate (100 repetitions), but does not imply that the system would be 100% accurate.

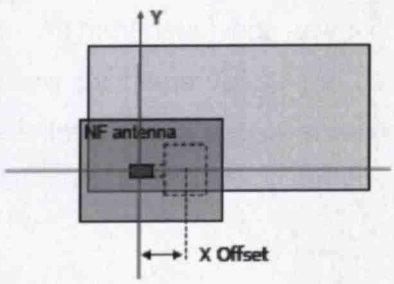
Triggering solution	Motion sensor
Response / Decision type	Determine direction
Decision making level (determine direction)	RFID Middleware level, custom algorithm
System Architecture	Reader – Custom Embedded Reader Software - RFID Middleware Server – Tracking application

Table 28. Description of solution

6.2 Conveyor belt application

This case is an application where the RFID system is reading and writing data to items moving on a conveyor belt. In conveyor belt applications the difficulty is providing accurate reads from fast moving objects and usually having only a small area for antenna field.

In this case the items were only 40mm apart from each other, which meant that the antenna field had to be designed to be less than that to avoid cross reading. Antenna used in this application generated about 20mm wide area for identification.



The time window for identification of each item was depended on the speed of the belt. At the point of reading belt speed was 1000cm per minute. Time left for identification was 120ms per tag (1000cm/min = 16cm/s=16mm/100ms). In the worst case a tag is coming to the field of view just after read cycle has started, which means that two cycles are need for reading reliably. Achieving constantly 60ms read times in production environment required careful optimization of gen2 parameters.

Table 29. Reading, conveyor speed vs. time

Conveyor speed	0,167	mm/ms
Read area length	20	mm
Read time window	60	ms

Table 30. Read rate in conveyor application

Total units passed	288
Successfull RFID reads	287
Read rate	**99,65 %**

One of the needs of the application was also to implement writing data into the tags, while moving on the conveyor belt. Reading in Gen2 requires only the process of inventory, but writing is a much more time consuming action as seen in the measurements in 0. Writing tags had to be achieved with conveyor speed 240cm/min, even though write point was placed in slowest part of conveyor belt.

Table 31. Writing, conveyor speed vs. time

	Conveyor speed	240	cm/min
	Conveyor speed	0,04	mm/ms
	Write area length	20	mm
	Write time window	250	ms

Calculating from the speed of the conveyor, we had to achieve 250ms writing time. In the previous lab tests 100ms was achieved, but this case required also dealing with more difficult production environment.

Table 32. Write rate in conveyor application

Total units passed	228
Write failed	4
Write rate	**98,25 %**

Table 33. Writing times in conveyor belt application

Max	Min	Average
828ms	157ms	239ms

The solution based on the fact that from the RFID reader's perspective, only one tag appears in the field at any given time, and for a predictable, controlled period, so the tag will have consistent access to power. The location of the tag was also very reliable because it always enters the same read zone. The reader can run at lower power because it is close to the tag, so other readers in the vicinity will not affect tag readability and the conveyor reader does not affect others. As a result of experiments it was noticed that writing to the tag was possible within the time window of 250ms with a successful write rate of 98.25%. Failed writes were most likely caused by variance in tag quality and therefore some of the tags would have required more power for writing – in some cases writing required several retries (write command interrupted in middle of writing), causing longer write times for tag (max 828ms).

Triggering solution	Photoelectric sensor
Response / Decision type	Reading / Writing tag data
Decision making level (writing commands)	Edge software
System Architecture	Reader – Edge software and PC – Manufacturing control system

6.3 Robotics application

In this case the RFID reading is implemented for identifying tagged items moved by an industrial robot and controlling the robot for placing the items. The robot arm moves objects through an antenna field without stopping and expects to receive a control command from a controlling application before the end of the movement path. Time frame for identification was 500ms and giving a command to the robot was <1s from start of reading in this case. The control signal determined where robot arm would place the item. One main question related to this case is reliability. Is it possible to achieve fast reading speeds in a continuous industrial process?

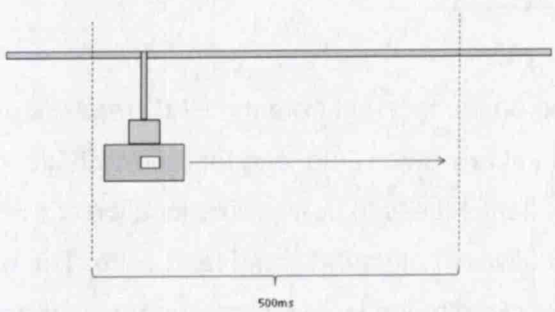


Figure 64. Robot movement through antenna field

In the solution reader was commanded to read for 500ms after the signal and return results to the edge software. Time measured with software timestamps was from beginning of read command to the actual response sent to the robot. Data was gathered from log files of the software and included 1845 repeats.

Triggering solution	Input signal form robot
Response / Decision type	Reading of tag
Decision making level (control signal to robot)	Edge software
System Architecture	Reader – Edge

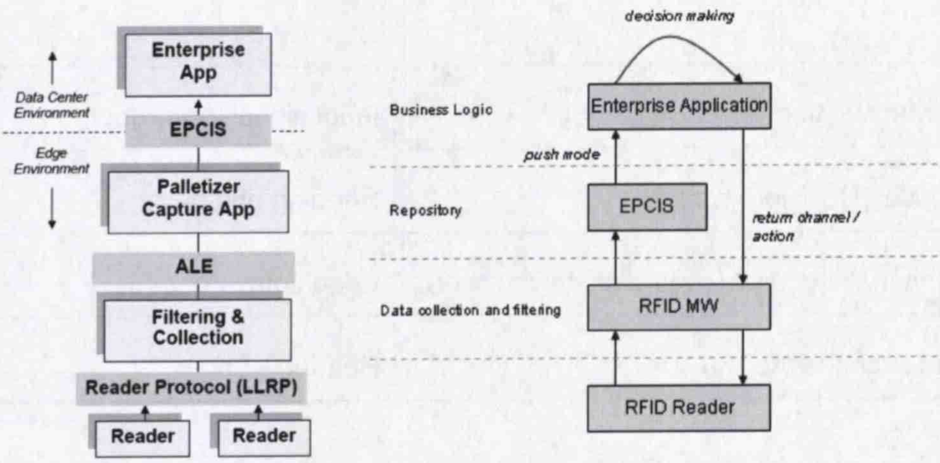
Responses	Required limit	Actual in production use
Read speed	<500ms	100% read rate with 500ms cycle for reading, (1845/1845)
Response time	<1000ms	509-574ms, AVG: 523ms (after reading started, reading for 500ms included)

Table 34. Results from response time in industrial robot case

The production result show that readers can perform reliably in an industrial process - not missing a single read in this batch of data. Reading the tags constantly within 500ms time windows was achieved easily. Response times for the robot command were also within the requirements on every single read. The RFID solution developed for this application was proven to be successful and able to meet real time requirements.

6.4 Return channel response from ERP

While gathering data from this case I wanted to find out what kind of delays were caused in the RFID system where response time was depended on an ERP systems transactions (such as SAP). Generally the response time depends on how far up in the logic decision making is done. The fastest response we can get directly from a reader and further up a message needs to travel the longer it will take time.



Measurements were done by investigating logs of RFID systems in production and running in real life production environment. The results of these measurements can give an idea how long the response times and delays are on different levels of RFID systems.

Level	Component used in tests
RFID MW	Vilant Device Manager 4.1
EPCIS	Vilant Basis 4
Enterprise Application	SAP

Data for these measurements were acquired from different software components. SAP was the ERP system in this case. Timestamps from different steps of operation were analyzed and delays could be calculated between the various steps.

	RFID MW to EPCIS	EPCIS to ERP	ERP decision making	ERP to RFID MW	Total
AVG delay	***554ms***	***88ms***	***304ms***	***251ms***	***1141ms***
MIN	*78ms*	*62ms*	*62ms*	*250ms*	*484ms*
MAX	*1009ms*	*94ms*	*1375ms*	*266ms*	*2625ms*

Table 35. Results of system level measurements

The measurement results show delay times between 484ms and 2625ms for feedback from ERP systems. Variations in delays can be explained by varying load of the applications, for example delay in the RFID MW may be increased as the amount of readers and read events increase, the response logic in ERP is also affected by the load of that system. It seems that the possibility for longest delay come from the ERP level. In conclusion of these results we can say that applications that use return channel decisions to give feedback to a low level system need to prepare for several seconds response time (here 2,6s at max), and can only expect minimum response times of several hundred milliseconds (here 484ms).

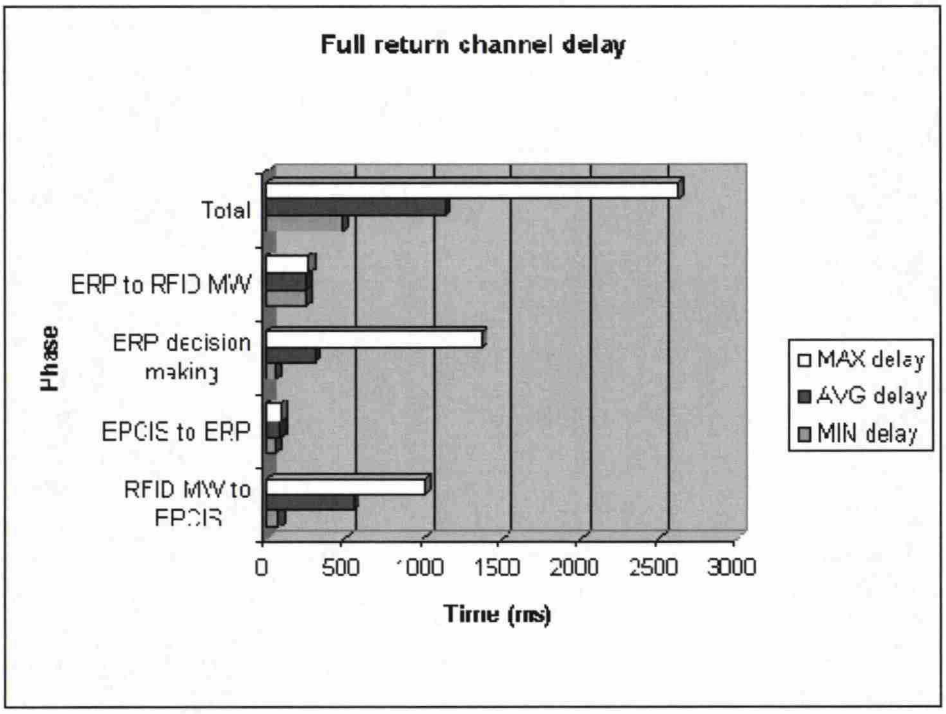


Figure 65. Full return channel delays from existing industrial RFID application

7 RESULTS

The test results and application case analysis are summarized here into a guideline for optimizing Gen2 RFID on the low level in real time applications.

Table 36. Optimal Gen2 settings for different tag identification cases

Application case	Main settings	Response time estimate, achievable	Comments
Direction sensing	Session 0, dense reader mode (if gate application), 4-channel plan	<100ms / tag	Physical tag and RF environment requires extra good planning. Multi tag environment is very difficult – direction sensing only works when amount of tags is low.
Fast single tag identification	Session 1 or higher, fast data rate, select function (inventory only needed tags), low Q-value, 4-channel plan (no LBT)	<20ms	Possibly dense reader mode to avoid channel change or force reader to single channel. Wide antenna field is helpful.
Multiple tag identification	Session 2/3, Q-value optimized (prefer dynamic)	<250ms / 100 tags	Pay attention to tag writing (headers so that they can be distinguished) Multi tags inventory is (relatively) slow with Gen2. Thousands of tags on pallet >> gate reading in full speed will be difficult. Consider if pallet tags can be read separately with select function.
Fast writing of tags	Select function, high data rates if possible, minimize environment noise	100-200ms / tag	RF environment should have relatively low noise.

Multiple readers	Sessions optimized between readers, 4-channel-plan, dense reader mode, sensors for triggering.	50-100ms / tag	

In comparison of different system architectures the test results also show some differences regarding response time. Here below is a guideline for estimating response times that we can expect from different levels.

Table 37. Optimal system architectures for different requirements

Response from	Response time estimate, achievable	Comments
ERP	>1s and up	Multiple database operations etc. may cause long delays
Middleware / EPCIS	<1s	Communication directly or though lower MW layer should be considered
Middleware / Device Management	<500ms	Depending on amount of hardware controlled by MW
Edge software	<100ms	Safe choice for most applications needed fast response
Reader level	<10ms	Consider difficulty of maintenance and updates of embedded software as a risk

8 CONCLUSIONS

The main purpose and objective of the thesis work was to find out what are the capabilities and constraints of Gen2 technology in terms of real time operability. The objectives focused around these questions: What are the real time capabilities of current RFID systems, how can fast response times and reliability be achieved with Gen2 RFID technology and what are the system designs to achieve these?

In conclusion we could say that fast response times are possible to achieve in Gen2 systems with careful optimization of the Gen2 protocol parameters for readers and by choosing the right architecture for right applications.

Single tag identification was calculated to be possible theoretically from 3.5 ms to 13 ms depending on the parameters may be adjusted by the users. The actual measurements verified that identification could be done at best in 7,7 ms. Average readings were in 8ms range and even with channel changes included still below 20 ms. We expected the from theoretical calculations that a single tag could be identified from a speed of about 50m/s, and in practice we found out that taking into account channel changes lowered the speed in real life closer to 100km/h. Dense reader mode, that does not required channel changes resulted in slower data rates and somewhat slower identification time than with fast data rates combined with a channel change.

A fast identification time in multi tag environment was achieved by using select-functionality when possible and by optimizing the Q-value and session value. Select-function could be used to minimize the amount of tag responses and in some application it can be used to single out only one tag at them time, which means that tag response will be as fast as in single tag measurements. If multiple tags have to be inventoried that can be optimized by Q-value and session to avoid collisions, but in general identifying hundreds or even thousands of tags will take longer time in Gen2-system. We got as a result for example 111 – 226 ms time for identifying 100 tags.

From system architecture point of view we found out that it is better to implement logic on the low levels in applications that need fast return channel responses (10-100 ms), such as robotics, actuator movement control, fast conveyor belts, fast moving tagged items (vehicles for example). This means programming the return channel responses so that they will come from embedded reader software or from edge software connected close to the actual hardware.

Middleware layer implemented with currently available middleware software is able to provide response between 100 ms and 500 ms, depending on load and the level of response – does it require database operations etc. However, it was not possible to test many of the commercially available middleware products, so these measurements considering middleware are only an indication of what the response might be. Common actions suitable for middleware level would be for example controlling traffic lights at dock doors and gates.

Response from business application level is slow and will take at least as much time as all the levels in total before it. Business application could be for example SAP or some other ERP system and it is basically impossible to estimate the time needed for operations on that level, but in one of the real world cases we got round trip response time of 500 ms to 2,6s for this level and that should give us an indication of what to expect.

The test cases and application cases describe various solutions to different types of cases in more detail. The test results from Gen2 reading tests show how setting Gen2 parameters affect response times and reliability. Measurement test cases and test results show the performance of Gen2 tag reading and also from system level responses in different cases. Comparing actual results to the theoretical calculations show that we could achieve response times quite close to the optimum. Results section summarizes a guideline how to achieve fast response times and reliability. The analysis of application cases show also how different architectures have performed in reality. The results section also has a rough guideline for selecting right architecture for different cases.

The real application cases introduced were all possible to implement with Gen2 technology and actually we should expect the technology to meet even faster response times than the cases presented in this thesis. Also the development of technology in future will probably increase the performance of Gen2 devices. However, after studying the background information of RFID and Gen2 technology, we came to the conclusion that current Gen2 UHF RFID is not really suitable for hard real time applications. For soft real time applications it is possible to find Gen2 solutions that meet even quite fast response requirements.

Target of this thesis was to determine the real performance of Gen2 RFID. The results gathered from measurements, test cases and data analysis from production cases gives a starting point for estimating response times in current UHF RFID technology and RFID systems. The results show clear numbers for response times in different situations and hopefully also helps in finding optimal solutions for real time related RFID systems. This thesis work can be used as a source in estimating requirements and solution possibilities to various Gen2 RFID systems in the future.

References

1. EPCglobal, Reader Protocol Standard Version 1.1, <URL http://www.epcglobalinc.org/standards/rp>, Referenced 1.8.2009, Published by EPCGlobal 2006

2. Roberts, C. M., Radio frequency identification (RFID),Computers & Security, 25, 18-26, 2006

3. .EPCglobal ,The EPCglobal Architecture Framework, <URL http://www.epcglobalinc.org/standards/ architecture/>,. Referenced 1.8.2009, Published by EPCGlobal 2005

4. Rolf Clauberg , RFID and Sensor Networks: From Sensor/Actuator to Business Application, , <URL http://www.zurich.ibm.com/pdf/sys/RFID_and_Sensor_Networks.pdf>, Referenced 1.8.2009, University of St. Gallen, Switzerland, Sept. 27, 2004

5. EPCglobal, The Application Level Events (ALE) Specification Version 1.0, <URL http://www.epcglobalinc.org/standards/ale>, Referenced 1.8.2009, Published by EPCGlobal 2006

6. Stephan Haller, Steve Hodges, The Need for a Universal Smart Sensor Network, <URL http://www.autoidlabs.org/uploads/media/CAM-AUTOID-WH-007.pdf> , Referenced 1.8.2009, Published by Auto-ID Centre 2002

7. Nirav Chokshi, Alan Thorne, Duncan McFarlane, Routes for Integrating Auto-ID Systems into Manufacturing Control Middleware Environments, <URL http://www.autoidlabs.org/uploads/media/CAM-AUTOID-WH026.pdf>, Referenced 1.8.2009, Published by Auto-ID Labs 2003

8. Duncan McFarlane, Networked RFID in Industrial Control: Current and Future, <URL http://www.autoidlabs.org/single-view/dir/article/6/54/page.html> , Referenced 1.8.2009, Published by Auto-ID Labs 2005

9. EPCglobal, Radio-Frequency Identity Protocols Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz – 960 MHz Version 1.0.9,

<URL http://www.epcglobalinc.org/standards/uhfc1g2>, Referenced 1.8.2009, Published by EPCGlobal 2005

10. RFID Journal, Manufacturing Gains in Efficiency, <URL http://www.rfidjournal.com/article/articleview/421> , Referenced 28.6.2008

11. Fusheng Wang and Peiya Liu, Temporal Management of RFID Data, <URL www.vldb2005.org/program/paper/wed/p1128-wang.pdf>, Referenced 1.8.2009, Published by Siemens Corporate Research

12. Finkenzeller, Klaus, RFID –Handbook: Radio-frequency Identifi cation Fundamentals and Applications, John Wiley & Sons, 2003, Chichester, 446, ISBN:0470844027

13. R. A. Kleist, T. A. Chapman, D. A. Sakai, and B. S. Jarvis. RFID Labeling - Smart Labeling Concepts & Applications for the Consumer Packaged Goods Supply Chain. Printronix, Inc., USA, CA, 2004, 389, ISBN:0976008610

14. Viestintävirasto, Määräys luvasta vapaiden radiolähettimien yhteistaajuuksista ja käytöstä, <URL www.ficora.fi/attachments/suomi_R_Y/1158858976905/Files/CurrentFile/Viestintavirasto15W2006M.pdf > Referenced 1.8.2009, Published by Viestintävirasto 2006

15. AIM Publication, Shrouds of Time, The history of RFID, <URL http://www.transcore.com/pdf/AIM%20shrouds_of_time.pdf>, Referenced 6.12.2008, Published by AIM Publication

16. Wikipedia, Real-time computing,<URL http://en.wikipedia.org/wiki/Real_time> , Referenced 6.12.2008

17. The RFID Handbook, RFID vs BAR CODE <URL http://www.rfidhandbook.blogspot.com/2004/11/rfid-vs-bar-code.html> , Referenced 17.12.2008

18. RFIDTribe, What is RFID? A Brief Introduction to RFID, <URL http://www.rfidtribe.com/home/index.php?option=com_content&task=view&id=433&Itemid=99999999> , Referenced 24.6.2008

19. Duncan McFarlane, Yossi Sheffi , The Impact of Automatic Identification on Supply Chain Operations, Cambridge University Engineering Department, Massachusetts Institute of Technology, <URL http://web.mit.edu/sheffi/www/selectedMedia/genMedia.sheffi-McFarlane.pdf> , Referenced 24.8.2008

20. Karthik Narayanan Moncombu Ramakrishnan,Performance Benchmarks for Passive UHF RFID Tags, Master's Thesis, College of Engineering, Guindy – Anna University, Chennai, India, 2003

21. Mieloo & Alexander, Whitepaper: RFID / EPC in Europe, <URL http://www.mielooandalexander.com/download/whitepaper/M&A_whitepaper_rfid_in_europe.pdf>, Referenced 1.8.2009, Published by Mieloo&Alexander 2006

22. ETSI EN 302 208-1 V1.2.1 (2007-07), Electromagnetic compatibility and Radio spectrum Matters (ERM); Radio Frequency Identification Equipment operating in the band 865 MHz to 868 MHz with power levels up to 2 W; Part 1: Technical requirements and methods of measurement, ETSI, 650 Route des Lucioles F-06921 Sophia Antipolis Cedex, FRANCE, 2007, 14p

23. Motorola USA, "RFID Readers", <URL http://www.motorola.com/business/v/index.jsp?vgnextoid=f9ebe90e3ae95110VgnVCM1000008406b00aRCRD> , Referenced 17.5.2008

24. EPCglobal, Tag Class Definitions, <URL http://www.epcglobalinc.org/standards/TagClassDefinitions_1_0-whitepaper-20071101.pdf> , Referenced 1.8.2008, Published by EPCglobal 2007

25. RFID Design Line, "RFID Basics: Backscatter Radio Links and Link Budgets", <URL http://www.rfdesignline.com/howto/202200135;jsessionid=3PN3IWTAWDTVCQSNDLPSKH0CJUNN2JVN?pgno=1> , Referenced 21.5.2008

26. ADCTECH, "Will your EPC Gen2 system be up to standard?", <URL http://www.adctech.com/documents%5Cwhitepapers%5CGen2SysStand_wp_web.pdf> , Referenced 24.5.2008

27. Pavel V. Nikitin, Membe, Steve Lazar, K. V. S. Rao, An Overview of Near Field UHF RFID, Intermec Technol. Corp, 26-28 March 2007, Grapevine, TX, USA, IEEE, 2007. p167-174. ISBN: 1-4244-1013-4

28. Rfid-handbook.de, “Operating principles of RFID systems”, <URL http://rfid-handbook.de/rfid/types_of_rfid.html> , Referenced 18.6.2008

29. UPM Raflatac, “RFID Products” <URL http://www.upmraflatac.com/asia/eng/RFIDProducts/ProductsbyMarketSegment/Pharma/> , Referenced 20.6.2008

30. B. S. Prabhu, Xiaoyong Su, Harish Ramamurthy, Chi-Cheng Chu, Rajit Gadh, WinRFID – A Middleware for the enablement of Radio Frequency Identification (RFID) based Applications, Wireless Internet for the Mobile Enterprise Consortium (WINMEC), UCLA, Los Angeles, CA, USA, 2005

31. UPU, Technology selection considerations and air interface standards. <URL http://www.upu.int/info_tech/en/2007-10-16_presentation12_technology_selection_considerations_and_air_interface_standards_en.pdf , Referenced 1.7.2008

32. ISO/IEC JTC 1 N8549, <URL http://isotc.iso.org/livelink/livelink/fetch/2000/2122/327993/755080/1054034/2541793/JTC001-N-8549.pdf?nodeid=6274634&vernum=0> , Referenced 1.7.2008

33. Pete Sorrells, Passive RFID Basics, , <URL http://www.ieechina.com/Upload/Tech/200407231602310890.pdf> , Referenced 13.7.2008

34. University of Boulder, The Electromagnetic Spectrum, , <URL http://lasp.colorado.edu/cassini/images/Electromagnetic%20Spectrum.jpg> , Referenced 13.7.2008

35. EPCglobal, Application Level Events 1.1(ALE 1.1) Overview Filtering & Collection, <URL http://www.epcglobalinc.org/standards/ale/ale_1_1-presentationOverview-20080305.pdf> , Referenced 30.7.2008, Published by EPCglobal 2008

36. Michael Maloni, Frank DeWolf, Understanding Radio Frequency Identification (RFID) and Its Impact on the Supply Chain, Penn State Behrend, Erie, PA, USA, 2006, <URL http://pserie.psu.edu/outreach/rfid/Documents/RFIDresearchPSU.pdf>

37. Kurt Menges, RFID Standards and Trends, Penn State Behrend, Erie, PA, USA, 2006, <URL http://www.behrend.psu.edu/outreach/rfid/Documents/conf_PDFs/RFID_Standards_and_Trends.pdf>

38. Information technology — Radio frequency identification for item management — Implementation guidelines – Part 3: Implementation and operation of UHF RFID Interrogator systems in logistics applications, ISO/IEC TECHNICAL REPORT, ISO/IEC JTC 1/SC 31/WG 4/SG 5 N 1862, 18-4-2005 ,<URL http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=45332>, Referenced 1.8.2008

39. John Falck, Spectrum needs for RFID, <URL http://isotc.iso.org/livelink/livelink/fetch/2000/2122/327993/327946/7320161/7320162/7321912/SC031-N-2498_-_Liaison_Report_-_ETSI_-_EU_REG.pdf?nodeid=7320093&vernum=0 > , Referenced 1.8.2008

40. Auto-ID Labs, Mission, <URL http://www.autoidlabs.org/mission/page.html> , Referenced 2.8.2008

41. EPCglobal, Guidelines on EPC for Consumer Products, <URL http://www.epcglobalinc.org/public/ppsc_guide/> , Rerefenced 2.8.2008, Published by EPCglobal

42. Daniel M. Dobkin, Daniel J. Kurtz, Overview of EPCglobal Class 1 Generation 2 and Comparison with 1st Generation EPCglobal Standards, <URL http://www.wj.com/documents/Articles_PDF/Overview_of_EPCglobal_Class_1_Generation_2_and_Previous_EPCglobal_Standards_1_FINAL.pdf> , Referenced 6.8.2008

43. Norman Abramson, THE ALOHA SYSTEM -AN0THER ALTERNATIVE FOR COMPUTER COMMUNICATIONS,1970, <URL http://stinet.dtic.mil/cgi-

bin/GetTRDoc?AD=AD707853&Location=U2&doc=GetTRDoc.pdf> , Referenced 6.8.2008

44. Wikipedia, Media Access Control, <URL http://en.wikipedia.org/wiki/Media_Access_Control> , Referenced 6.8.2008

45. Wikipedia, ALOHAnet , <URL http://en.wikipedia.org/wiki/ALOHAnet> , Referenced 6.8.2008

46. National Instruments, The State of Radio Frequency Identification (RFID): New EPC Gen2 RFID Standard Emerges, <URL http://zone.ni.com/devzone/cda/tut/p/id/4300> , Referenced 3.8.2008

47. Kin Seong Leong, Mun Leng Ng, Membe, Peter H. Cole, The Reader Collision Problem in RFID Systems, Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications, 2005. MAPE 2005. IEEE International Symposium on Volume 1, Issue , 8-12 Aug. 2005, p658 – 661, Vol. 1, Digital Object Identifier 10.1109/MAPE.2005.1617996

48. EPCglobal, Low Level Reader Protocol (LLRP), Version 1.0.1, <URL http://www.epcglobalinc.org/standards/llrp/llrp_1_0_1-standard-20070813.pdf>, Referenced 8.8.2008, Published by EPCglobal 2007

49. Impinj, LLRP—Reader Control Simplified, <URL http://www.impinj.com/uploadedFiles/RFID/Case_Studies_White_Papers/Impinj-LLRP_data_sheet(singlespages-web).pdf>, Referenced 8.8.2008

50. Dang Nguyen Duc, Jaemin Park, Hyunrok Lee, Kwangjo Kim, Enhancing Security of EPCglobal Gen-2 RFID Tag against Traceability and Cloning, The Institute of Electronics, Information and Communication Engineers Hiroshima, Japan, Jan. 17-20, 2006, <URL http://caislab.icu.ac.kr/Paper/paper_files/2006/duc-scis06.pdf>, Referenced 9.8.2008

51. Dale R. Thompson, Neeraj Chaudhry, Craig W. Thompson , RFID SECURITY THREAT MODEL, University of Arkansas, Fayetteville, AR, USA, 2006, <URL http://comp.uark.edu/~drt/pubs/2006/rfid-threats-alar-060303.pdf> , Referenced 9.8.2008

52. Wei Wang, Duncan McFarlane, James Brusey, Timing Analysis of Real-Time Networked RFID Systems,<URL http://ivs.cs.uni-magdeburg.de/bs/tagungen/paper/rtn05S4_wang-RTRFID.pdf> , Referenced 10.8.2008

53. Auto-ID Labs, Networked Real-Time RFID System, <URL http://www.autoidlabs.org.uk/realtimerfid.html> , Referenced 10.8.2008

54. Herman Kopetz, Real Time Systems: Design Principles for Distributed Embedded Applications, Norwell, MA, USA, Kluwer Academic Publishers,1997, ISBN: 0-7923-9894-7

55. Vilant Systems Oy, Content from web pages, <URL http://www.vilant.com/>, Referenced 1.6.2008

56. Dennis E. Brown, RFID Implementation, McGraw-Hill Professional, 2006 , ISBN-13:978-0-07-226324-4

57. Harold G. Clampitt, RFID Certification Textbook, American RFID Solutions; 2007, ISBN-13: 978-0-9794285-0-0

58. Interview, Product Manager Reino Aavikko, Vilant Systems Oy

59. Impinj,RFID Inside Track Article, <URL http://www.impinj.com/news-events/Newsletters/Newsletter_3/rfid-newsletter-November-2007.aspx> , Referenced 2.7.2009